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STEADY-STATE COMBUSTION OF NONMETALLIZED COMPOSITE SOLID PROPELLANT

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FOREWORD

This is an interim report covering the work completed under Contract F44620-74-C-0080 for the period 1 May 1974 through 30 June 1975. Publication of this report does not constitute Air Force approval of the findings or conclusions contained herein. It is published only for the exchange of data and stimulation of ideas.

The program is monitored by Capt. L. R. Lawrence, Jr., of the Air Force. Mr. G. F. Mangum is the Project Director and Dr. M. Miller is the Program Manager.

G. F. Mangum
Project Director

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ABSTRACT

Monodisperse BDP combustion model was extended to nonmetallized propellants with mixed, polydisperse oxidizers by embedding monodisperse model in statistical framework including mixture ratio effects. Basically, polydisperse propellant is "disassembled and rearranged" to form sequence of monodisperse pseudo-propellants whose rates are computed via monodisperse model. Reassembly provides real propellant's burning rate. Approach provides information pertaining to distribution of regression rates and surface structure among different size ox. particles. Preliminary results suggest that significant factor in rate increases wrought by introduction of small oxidizer modes is mixture ratio alterations in larger modes.

Hydraulic T-burner analog was constructed and employed to visualize vent flow phenomena. Studies showed that flow enters vent with axial momentum and that that momentum is partially transformed to vent into Karman vortex sheet. Fact that flow enters vent with axial momentum invalidates boundary condition of Culick analysis for flow turning gain; "correct" boundary condition leads to null vent gain. Experimental facts consistent with proof that in formal one-dimensional flow vent gain violates second law of thermodynamics.

Logical and consistent way to reduce solid rocket data when pressure-time history is not neutral was derived. Since current techniques are not self-consistent in this situation, these results open door to reclamation of performance data heretofore rejected.

INTRODUCTION

Since 1972 when Culick[1] first found that formal analysis of the linearized, one-dimensional equations of change led to acoustic/mean flow interactions (A/MFI), the rather surprising flow turning gain associated with a T-burner's vent has been regarded skeptically. The situation was not improved by the appearance of another "theory" predicting different A/MFI[2] and indecisive results obtained from T-burner tests aimed at evaluating A/MFI. The situation in 1973* is described in some detail by Shoner[3].

It is not surprising that Culick's one-dimensional results conflict with results stemming from the theory developed by McClure, Hart, and Cantrell[5] in an area where mixing and viscous effects are important. Culick's theory implicitly includes mixing while MHC's theory explicitly (through the inviscid media assumption) disallows mixing. Clearly, what is required is qualitative knowledge of the flow phenomena so that "intelligent" modeling of A/MFI can be accomplished. A cost effective approach to obtaining qualitative information about multi-dimensional nonsteady flows is to employ the hydraulic analogy. Accordingly, a proposal was prepared and submitted to AFOSR with the expressed purpose of examining the vent region flow in a T-burner with the hydraulic analogy.

Since 1970 steady-state composite propellant combustion modeling has been dominated by the Beckstead, Derr, Price (BDP) model[6]. Although the basic model applied solely to additive-free propellant with spherical, monodisperse oxidizer, Cohen, Derr, and Price[7] extended the model to propellants with aluminum and bimodal oxidizer. Sammons[8] subsequently extended the model to propellants with polydisperse oxidizer.

Since composite solid propellant is a random packing of solid particles filled with binder and the deflagration wave traverses the solid, the burning surface must also possess random structure. Because of the discrete particulate nature and random structure of the burning surface, a classical steady state where state variables are invariant in time cannot exist; at any fixed time spatial variations of state variables are random to some length scale; at any fixed position relative to the burning surface the state variables are random in time to some time scale. Consequently, steady-state combustion can only mean that statictical means are stationary in time.

In the monodisperse BDP model the random, nonsteady phenomena at the burning surface is "averaged" into a mean state in a particle's life. Treating this state as quasi-steady and applying mass and energy conservation, kinetics principles, etc., an implicit "relation" for burning rate is obtained. No derivation has been given for the averaging procedure. Cohen, Derr, and Price[7] extended the model to bi-modal distributions by assuming <u>all</u> particle sizes burn at the

*The situation in 1974 was not greatly changed; see discussion in Reference 4.

same rate. This seems highly improbable. On the other hand, Sammons[8] extended the model to polydispersions by apparently assuming that the polydispersion could be averaged into a single particle. No derivation was given for this averaging procedure.

In 1973 Glick[9][10] advanced a statistical combustion modeling formalism that applied to polydisperse situations and eliminated the aforementioned approximations. Consequently, a proposal was prepared and submitted to AFOSR with the expressed purpose of embedding the basic BDP combustion model in this statistical formalism.

These separate proposals were ultimately combined into a single program with the following objectives:

- Construct a hydraulic analogue of a T-burner utilizing a water table.
- Investigate the flow pattern in the vent region of the T-burner analogue to determine whether or not acoustic energy is convected out the vent.
- Compare the experimental results in qualitative fashion with the predictions of present T-burner theories.
- Adapt the Beckstead, Derr, Price combustion model as modified by Sammons to the contractor's statistical combustion model. Investigate the properties of the resulting model as it pertains to propellants with polydispersions of spherical, mixed oxidizers.

This program was monitored, in the best sense of the word, by Capt. L. R. Lawrence, Jr. This report describes in detail the work that was accomplished under this program.

STEADY-STATE COMBUSTION OF NONMETALLIZED COMPOSITE SOLID PROPELLANT

Development of Theory

The most obvious feature of composite solid propellants is their heterogeneous structure. Since high specific impulse is desirable for propulsion systems, total solids content is generally as large as possible. Since composite propellant is essentially a packing of solid particles filled with binder, high total solids content demands a dense packing. To achieve a dense packing, the particles must be polydisperse with a broad range of particle sizes so that the smaller particles can fill the voids in the packing of the larger particles. Therefore, virtually all practical propellants are polydisperse. In the past ammonium perchlorate (AP) was the preferred oxidizer specie. Consequently, propellants with mixed oxidizers were rare. However, recent emphasis on reduced visual

signature has aroused interest in oxidizers other than AP and propellants with non-AP oxidizer, mixtures of non-AP oxidizers, and AP and non-AP mixtures are being explored. Therefore, realistic combustion modeling must consider, in the least, propellants with mixed, polydisperse oxidizers.

Composite propellants are created by mixing their several ingredients together. Therefore, a randomly packed, particulate structure is expected above some length scale. Since the deflagrating surface transverses the solid, the arrangement/structure of oxidizer particles on the burning surface must also be random above some length scale. Because of this randomness and the discontinuous chemistry wrought by heterogeneity, composite propellant combustion is never steady-state in the sense that state variables are invariant in time; at any time state variables are spatially random above some length scale; at any fixed position relative to the mean burning surface state variables vary randomly in time above some time scale. Consequently, analysis of "steady-state" combustion must be directed toward the determination of state variable means and distributions.

Consider now a large, quasi-planar deflagrating surface of composite solid propellant (see Figure 1). Application of mass conservation to the control surface yields

$$dm_{cv}/dt = \oint_{S_b} m''dS - \oint_{S_p} m''dS \qquad (1)$$

Experience shows that when $dp = dT_i = 0$ $\lim_{S_p \to \infty} dm_{cv}/dt = 0$. Consequently, for steady-state combustion

$$\oint_{S_p} m''dS = \oint_{S_b} m''dS \qquad (2)$$

Applying the mean value theorem for integrals to the LHS of Eq. (1) yields

$$\overline{m}_t = \oint_{S_b} m''dS/S_p = \overline{r}\,\rho_t \qquad (3)$$

The surface S_b may be visualized as a jigsaw puzzle-like arrangement of oxidizer particle/fuel surface pairs. For composite propellant with polydisperse, mixed oxidizers, some of these oxidizer particle/fuel surface pairs will have the same particle diameter and specie. Therefore, rearrange the oxidizer particle/fuel surface pairs so that those with common particle diameters and species are neighbors. This rearrangement creates a sequence of monodisperse propellant subsurfaces. If it is assumed that combustion of all oxidizer particle/fuel surface pairs are independent, the deflagration rate of any monodisperse subsurface can be computed by application of any monodisperse combustion (BDP for example) model. Consequently, proper summation of these subsurface rates should yield the burning rate of composite propellant with mixed, polydisperse oxidizer.

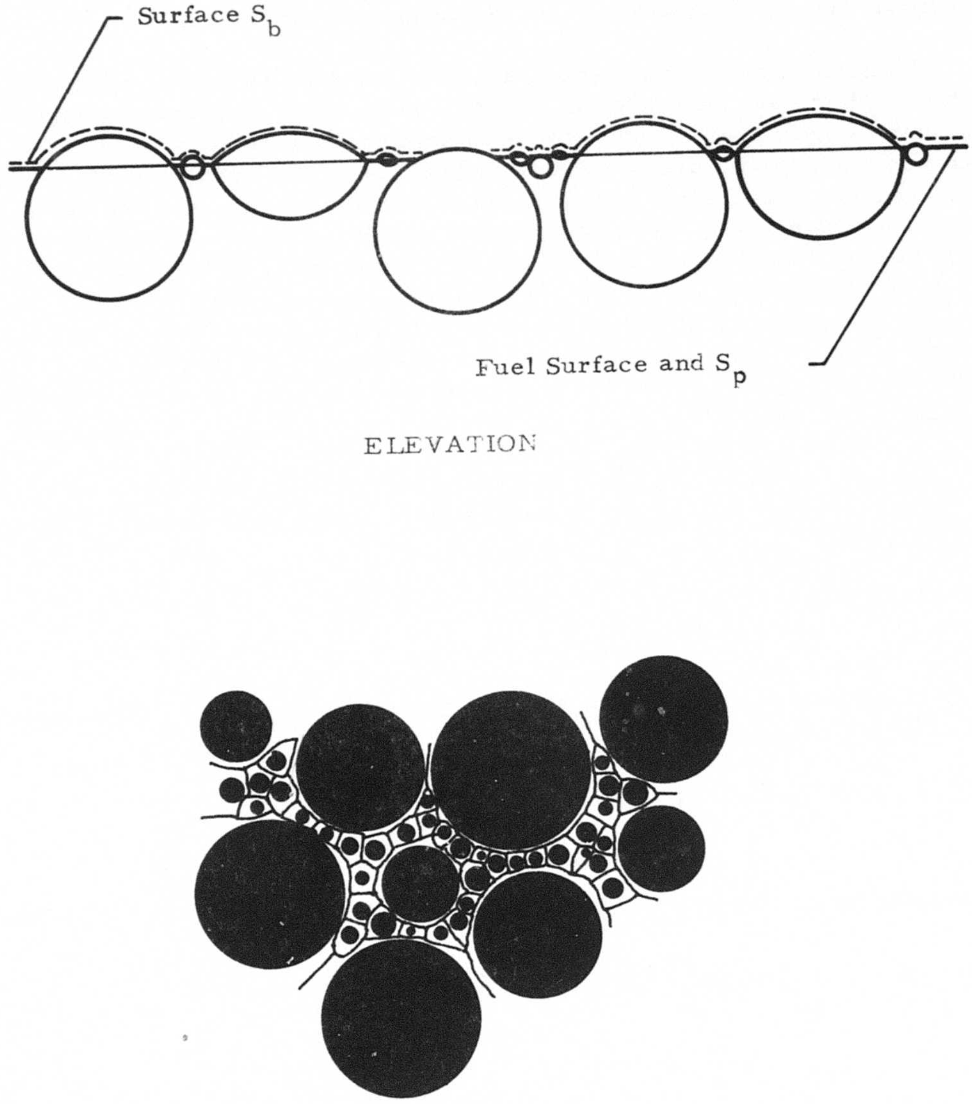

Figure 1. Schematic of Propellant Surface

To accomplish this approach rearrange the burning surface's oxidizer particle/fuel surface pairs into Q monodisperse subsurfaces. Then Eq. (3) becomes

$$\overline{m}_t'' = \sum_{i=1}^{Q} \Big(\sum_{k=1}^{s} \oint_{\Delta S_{b,d,k}} m''_{d,k}\, dS\Big)/S_p \tag{4}$$

where $\Delta S_{b,d,k}$ is the portion of S_b occupied by and $m''_{d,k}$ is the mass flux from oxidizer particle/fuel surface pairs possessing oxidizer particles with $D \leq D \leq D + \Delta D$ and specie k. Application of the mean value theorem for integrals to the RHS of Eq. (4) yields

$$\overline{m}_t'' = \sum_{i=1}^{Q} \Big(\sum_{k=1}^{s} \overline{m}''_{d,k}\, \Delta S_{b,d,k}\Big)/S_p \tag{5}$$

The term $\overline{m}''_{d,k} \Delta S_{b,d,k}$ is the mass flow of products from the monodisperse subsurface $\Delta S_{b,d,k}$. Therefore,

$$\overline{m}''_{d,k}\, \Delta S_{b,d,k} = \overline{m}''_{p,d,k}\, \Delta S_{p,d,k} \tag{6}$$

where $\overline{m}''_{p,d,k}$ is the mean mass flux (based on planar area) from the monodisperse subsurface $\Delta S_{b,d,k}$ and $\Delta S_{p,d,k}$ is the projection of $\Delta S_{b,d,k}$ on S_p.

If $\Delta N_{p,d,k}$ is the number of oxidizer particles on S_p with $D \leq D \leq D = \Delta D$ and specie k per unit area of S_p,

$$\Delta S_{p,d,k}/S_p = \Delta \bar{S}_{p,d,k}\, \Delta N_{p,d,k} \tag{7}$$

where $\Delta \bar{S}_{p,d,k}$ is the average planar surface for an oxidizer particle/fuel surface pair possessing oxidizer particles with $D_i \leq D_i \leq D_i + \Delta D$ and specie k.

Define a distribution function $F_{p,d,k}$ such that

$$\Delta N_{p,d,k} = N F_{p,d,k}\, \Delta D \tag{8}$$

Then combining Eqs. (5) - (8) yields

$$\bar{m}_t = N \sum_{k=1}^{S} \left(\sum_{i=1}^{Q} \bar{m}''_{p,d,k} \Delta \bar{S}_{p,d,k} F_{p,d,k} \Delta D \right) \tag{9}$$

Passing to the limit of the sum on i as $Q \to \infty$ yields

$$\bar{m}''_t = N \sum_{k=1}^{S} \oint_D \bar{m}''_{p,d,k} \Delta \bar{S}_{p,d,k} F_{p,d,k} \, dD = \bar{r} \rho_t \tag{10}$$

Equation (10) is a statistical formalism that enables the mean burning rate of propellant with mixed, polydisperse oxidizers to be computed from the mean burning rates ($\bar{m}_{p,d,k} = \bar{r}_{d,k} \rho_{t,d,k}$) of the sequence of monodisperse psuedo-propellants that "compose" it <u>IF THE COMBUSTION OF EACH OXIDIZER PARTICLE/FUEL SURFACE PAIR IS INDEPENDENT.</u> This approach permits consideration of mixed oxidizers and avoids the requirement that a single particle be selected to represent a polydispersion. Since a polydispersion is represented <u>as</u> a polydispersion, information concerning the variation of surface geometry, temperature, regression rate, etc. can also be computed.

The next step is to investigate the statistical characteristics of the burning surface and thereby relate $\Delta \bar{S}_{p,d,k}$, $F_{p,d,k}$, and the properties of the monodisperse psuedo-propellants to propellant formulation variables. Assuming that the statistical characteristics of the random packing are homogeneous and isotropic, the statistical characteristics of surface S_p can be explored within the propellant. Figure 2 illustrates a random polydisperse packing schematically. Clearly, particles with $D \leq D \leq D + dD$ must lie within $z = \pm D/2$ to intersect plane S. Therefore, if $dN_{v,d}$ is the number of particles per unit volume with $D \leq D \leq D + dD$, the number of these particles that intersect S per unit area of S is

$$dN_{p,d} = dN_{v,d} \, D \tag{11}$$

The volume fraction of spherical particles with diameter D is

$$d\zeta_d = (\pi D^3/6) \, dN_{v,d} \tag{12}$$

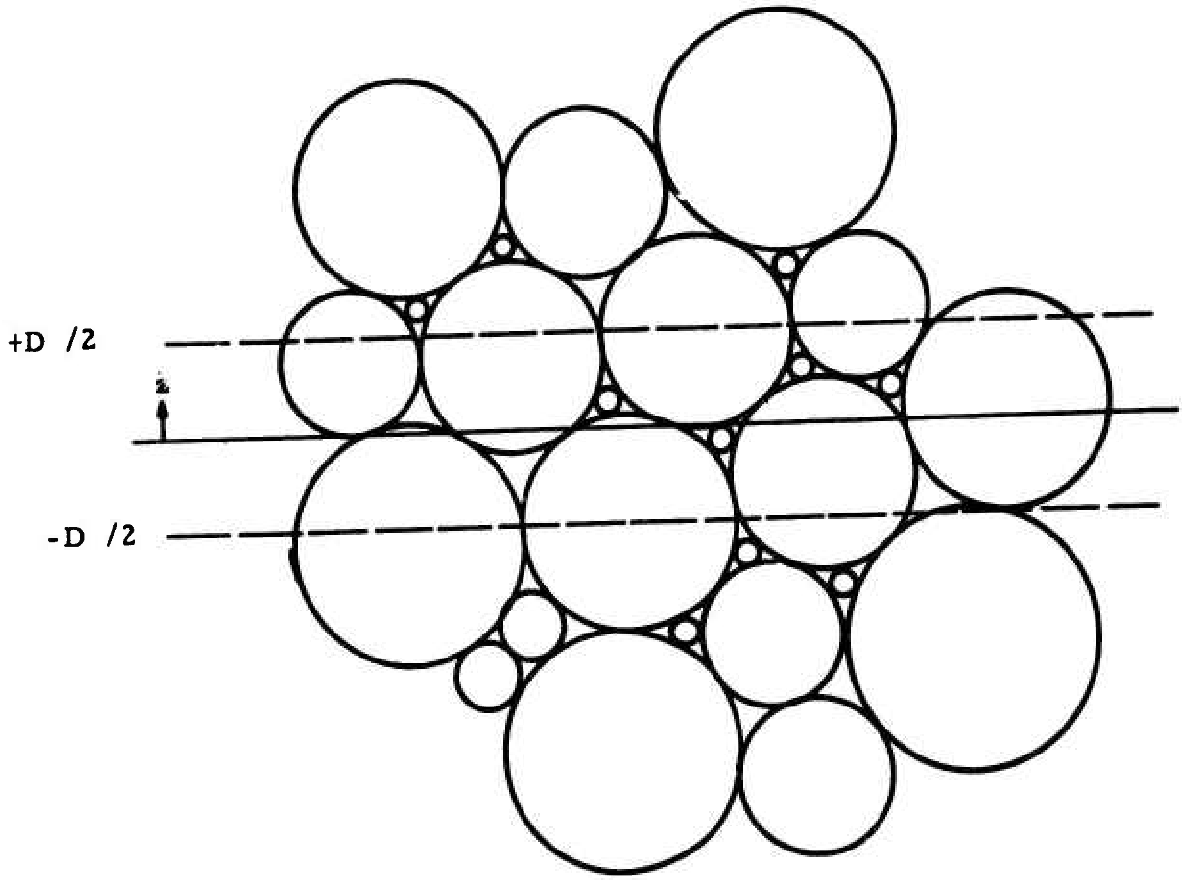

Figure 2 Schematic of Particle Packing

Therefore,

$$dN_{p,d} = (6/\pi D^2)\, d\,\zeta_d \tag{13}$$

If the number fraction of particles with $D \le D \le D + dD$ and species k in the propellant is $\eta_{d,k}$,* the number of these particles per unit area of S is

$$dN_{p,d,k} = (6/\pi D^2)\, \eta_{d,k}\, d\,\zeta_d = (6/\pi\, D^2) d\,\zeta_{d,k} \tag{14}$$

Now move the plane a distance Δz. The volume of oxidizer particles with $D \le D \le D + dD$ in the swept volume is

$$d\,V_d = d\,\zeta_d\; S\,\Delta z \tag{15}$$

However, the statistical characteristics are homogeneous and isotropic. Therefore, this volume is also swept out by intersections of S with oxidizer particles having $D \le D \le D + dD$. Since $dS_{p,d} = (\pi\, \overline{D}_d/4)\, dN_{p,d}$,

$$d\,V_d = (\pi\, \overline{D}_d^2/4)\, dN_{p,d}\; \Delta z \tag{16}$$

Combining Eqs. (13), (15), and (16) yields the mean particle intersection diameter

$$\overline{D}_d = \sqrt{2/3}\, D \tag{17}$$

Therefore, the <u>average</u> oxidizer particle intersection area is

$$\Delta\overline{S}_{o,d,k} = \pi\, D_{d,k}^2/6 \tag{18}$$

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*Note that $\sum_{k=1}^{s} \eta_{d,k} = 1$. Since all these particles have same diameter, $\eta_{d,k}$ is also a volume fraction.

It is important to note that $\overline{D}_d$, $dN_{v,d}$ and $dN_{p,d}$ are functions of D alone. This means that statistical characteristics of the monodisperse cuts in a polydisperse propellant are the same as those in a monodisperse propellant. In short, each monodisperse cut behaves as if it alone occupied the propellant. Notice the similarity to mixtures of perfect gases.

The mean statistical characteristics of the fuel surface in each monodisperse cut of oxidizer fuel surface pairs cannot be determined exactly because it requires a statistical determination of how the smaller particles pack inside the packing of larger particles. This information is unavailable. Therefore, approximations must be introduced. Examination of the characteristics of regular geometric packings [11] suggests that the mean volume of fuel associated with a particle should be roughly proportional to its surface or $\overline{\Delta V}_{f,d} \propto D^2$. However, to allow for some variation assume

$$\overline{\Delta V}_{f,d} = C\, D^n \tag{19}$$

where n is a parameter to be determined experimentally. Since oxidizer volume is proportional to D^3, $d(O/F)/dD \gtrless 0$ when $n \gtrless 3$. Particle diameter alone is important in a packing. Therefore, $\overline{\Delta V}_{f,d,k} = \overline{\Delta V}_{f,d}$.

The volume fraction of fuel associated with particles having $D \le D \le D + dD$ and species k is

$$dV_{f,d} = \overline{\Delta V}_{f,d}\; dN_{v,d} \tag{20}$$

The volume fraction of fuel in the real propellant is $1 - \zeta_o$; it is also the integral of Eq. (20) over all particle diameters. Employing this fact and Eqs. (12) and (20) yields after integrating over all diameters

$$C = [\pi\,(1 - \zeta_o)/6]/\oint_D D^{n-3}\; d\,\zeta_d \tag{21}$$

With both particle diameter and mean volume of fuel associated with that particle diameter "known" the volume and mass fractions and the density of a psuedo-propellant formed from mono-diameter and specie oxidizer particle/fuel surface pairs can be computed. The volume fraction is $\Delta V_{o,d,k} / (\Delta V_{o,d,k} + \Delta V_{f,d,k})$ so

$$\zeta^*_{d,k} = (1 + 6CD^{n-3}/\pi)^{-1} \tag{22}$$

The mass fraction is $\overline{\Delta m}_{o,d,k}/(\overline{\Delta m}_{o,d,k} + \overline{\Delta m}_{f,d,k})$ so

$$\alpha^*_{d,k} = [1 + 6C\rho_f D^{n-3}/(\pi\ \rho_{o,k})]^{-1} \tag{23}$$

The pseudo-propellant's density is

$$\rho^*_{d,k} = \rho_{o,k}\ \zeta^*_{d,k}/\alpha^*_{d,k} \tag{24}$$

Since $\zeta^*_{d,k} = S^*_{o,d,k}/S^*_{p,d,k} = \Delta\bar{S}_{o,d,k}/\Delta\bar{S}_{d,k}$, Eq. (18) becomes

$$\Delta\bar{S}_{d,k} = \pi D^2/(6\ \zeta^*_{d,k}) \tag{25}$$

The mass flux in Eq. (10) corresponds to the mean mass flux stemming from combustion of psuedo-propellant. Therefore,

$$\bar{m}''_{p,d,k} = \bar{m}''^*_{d,k} = \bar{r}^*_{d,k}\ \rho^*_{d,k} \tag{26}$$

The only tasks remaining are to relate $F_{p,d,k}$ and $d\,\zeta_{d,k}$ to the independent propellant formulation variables $\alpha_{k,j}$, $F_{k,j}$, M_k, and s. The volume fraction of oxidizer specie k with diameter D is defined as

$$d\,\zeta_{d,k} = d\,V_{o,d,k}/V_t \tag{27}$$

Since $dV_{o,d,k} = dm_{o,d,k}/\rho_{o,k}$ and $V_t = m_T/\rho_t$

$$d\,\zeta_{d,k} = (d\,m_{o,d,k}/m_t)\,(\rho_t/\rho_{o,k}) \tag{28}$$

However, $F_{k,j} = dm_{o,d,k,j}/(m_{o,k,j}\, dD)$ and $dm_{o,d,k} = \sum_{j=1}^{M_k} dm_{o,d,k,j}$

Therefore,

$$d\zeta_{d,k} = (\rho_t/\rho_{o,k}) \sum_{j=1}^{M_k} \alpha_{k,j}\, F_{k,j}\, dD \tag{29}$$

Since $dV_{o,d} = \sum_{k=1}^{s} dV_{o,d,k}$

$$d\zeta_d = \sum_{k=1}^{s} (\rho_t/\rho_{o,k})\, F_k\, dD \tag{30}$$

where

$$F_k = \sum_{j=1}^{M_k} F_{k,j}\, \alpha_{k,j} \tag{31}$$

Since $\zeta_o = V_o/V_t$, $V_o = \sum_{k=1}^{s} \sum_{j=1}^{M_k} V_{o,k,j}$, and $V = m/\rho$,

$$\zeta_o = \rho_t \sum_{k=1}^{s} \sum_{j=1}^{M_k} (\alpha_{k,j}/\rho_{o,k}) \tag{32}$$

Since $\rho_t = (V_t/m_t)^{-1}$, $V_t = \sum_{k=1}^{s} \sum_{j=1}^{M_k} V_{o,k,j} + V_f$, and $V = m/\rho$,

$$\rho_t = \left[\rho_f^{-1} + \sum_{k=1}^{s} \sum_{j=1}^{M_k} (\rho_{o,k}^{-1} - \rho_f^{-1})\, \alpha_{k,j}\right]^{-1} \tag{33}$$

By definition $NF_{p,k,d}\ dD = dN_{p,d,k}$. Employing Eq. (14) it is seen that

$$NF_{p,k,d}\ dD = 6\ d\,\zeta_{d,k}/(\pi\ D^2) \tag{34}$$

Employing this result and Eqs. (25) and (30), Eq. (10) can be rewritten as

$$\bar{r}\rho_t = \overline{m}''_t = \rho_t \sum_{k=1}^{s} \rho_{o,k}^{-1} \oint_D (\overline{m}''^{*}_{d,k}/\zeta^{*}_{d,k})\ F_k\ dD \tag{35}$$

Therefore

$$\bar{r} = \sum_{k=1}^{s} \rho_{o,k}^{-1} \oint_D (\overline{m}''^{*}_{d,k}/\zeta^{*}_{d,k})\ F_k\ dD \tag{36}$$

Eqs. (21 - 24), (31 - 33), and (36) put $\bar{r}$ in terms of real propellant data. Since interest is focused on the BDP model herein,

$$\overline{m}''^{*}_{d,k} = \overline{m}''_{BDP}\ (D,\ \alpha^{*}_{d,k},\ \rho^{*}_{d,k},\ \zeta^{*}_{d,k},\ \text{etc.}) \tag{37}$$

Modifications to BDP Model

The reason for polydisperse propellants is high total solids. Consequently, with "real" propellants the BDP model must operate in the $\zeta_o \approx 1$ regime. Unfortunately, examination of the model[6] shows that the b parameter (mean distance from center of oxidizer particle to center of binder separating particles) is given by

$$b = D\left[1 + \sqrt{3/2}\,(\delta/D)\right] / \sqrt{6} \tag{38}$$

where

$$\delta/D = [\pi/(6\zeta_o)]^{1/3} - (2/3)^{1/3} \tag{39}$$

Clearly, as ζ_o approaches unity, both δ/D and b must approach zero with the provisio that $\delta/D > 0$ and $b > 0$. Examination of Eq. (39) shows that δ/D changes sign at $\zeta_o \approx 0.785$. Consequently, Eqs. (38) and (39) and hence the BDP model cannot be employed for propellants with $\zeta_o \geq 0.785$. This represents no difficulty for monodisperse propellants because packing considerations limit ζ_o to values below this limit.[11] However, this is a very real difficulty with monodisperse psuedo-propellants.

The aforementioned difficulty occurs because the fuel surface of an oxidizer particle/fuel surface pair is assumed to be annular with $D_i = \overline{D}$ and $D_o = 2b$. However, in reality the binder surface is not an annulus but an irregular quadrilateral. Consequently, this assumption "loses" the fuel in the corners between the quadrilateral and the "inscribed" annulus. The simplest way to overcome this difficulty is to assume that b is the dimension of an annulus possessing the fuel surface associated with the mean oxidizer particle/fuel surface pair. In other words, b is defined by

$$\pi b^2 - \pi \overline{D}^2/4 = \Delta \overline{S}_f \tag{40}$$

The fraction of planar surface occupied by fuel is $1 - \zeta_o$. The number of particles/unit planar surface is given by Eq. (13). Therefore,

$$\Delta \overline{S}_f = (1 - \zeta_o)\, \pi D^2 / (6\zeta_o) \tag{41}$$

$$b = D/\sqrt{6\zeta_o} \tag{42}$$

and

$$\delta/D = (\zeta_o^{-1/2} - 1) / \sqrt{6} \tag{43}$$

Examination of the BDP computer program[12][13] shows that the FORTRAN expression employed for δ/D is not equivalent to Eq. (39) but represents

$$\delta/D = [\pi/(6\zeta_o)]^{1/3} - (2/3)^{1/2} \tag{44}$$

This expression is positive for $\zeta_o < 0.961$.

Figure 3 compares Eqs. (39), (43), and (44). It is seen that Eq. (43) has correct behavior for $\zeta_o \approx 1$ and agrees well with Eq. (39) for $\zeta_o \approx 0$.

Numerical tests were made to determine the effect of oxidizer mass fraction on burning rate. Tests were made with both Eqs. (38) (44) (denoted as BDP) and (42) (43) (denoted as Mod. BDP). Figure 4 presents results when D = 1 μ and p = 932 psi. It is clear that the solutions are discontinuous at both high and low mass fractions for both normal and modified BDP models. For oxidizer mass fractions greater than the upper discontinuity point and less than the lower discontinuity point, the models gave negative values for the diffusion flame standoff distances in both cases. Consequently, the difficulty appears to stem from the Burke-Schumann solution. Since the BDP model with the single term approximation to the Burke-Schumann solution was employed herein and Sammons multiple term version showed no evidence of discontinuities at a mass fraction of 0.86,[13] this defect can probably be remedied by employing the Sammons version of the BDP model. However, we did not have this version. Consequently, another remedy was sought. Because the diffusion flame standoff distances increased rapidly to very large values when the discontinuities were approached from the other direction, a negative diffusion flame standoff distance was replaced by a very large value whenever it occurred. This gives continuity with intermediate mass fraction results. Figure 5 illustrates rate versus mass fraction results with this modification.

Calculations at D = 100 μ and p = 932 psi exhibited behavior similar to the aforementioned. However, as will be observed below, the aforementioned results did not completely eliminate "discontinuous" behavior.

Implementation of Polydisperse BDP Model

The modified monodisperse BDP combustion model was extended to non-metallized propellants with a polydisperse oxidizer by embedding the model in the previously described statistical framework. A complete listing of the computer program and a description of its use with a sample problem is provided in Appendix A.

Since parametric studies were anticipated, a log normal distribution of oxidizer particle size was assumed for each mode.

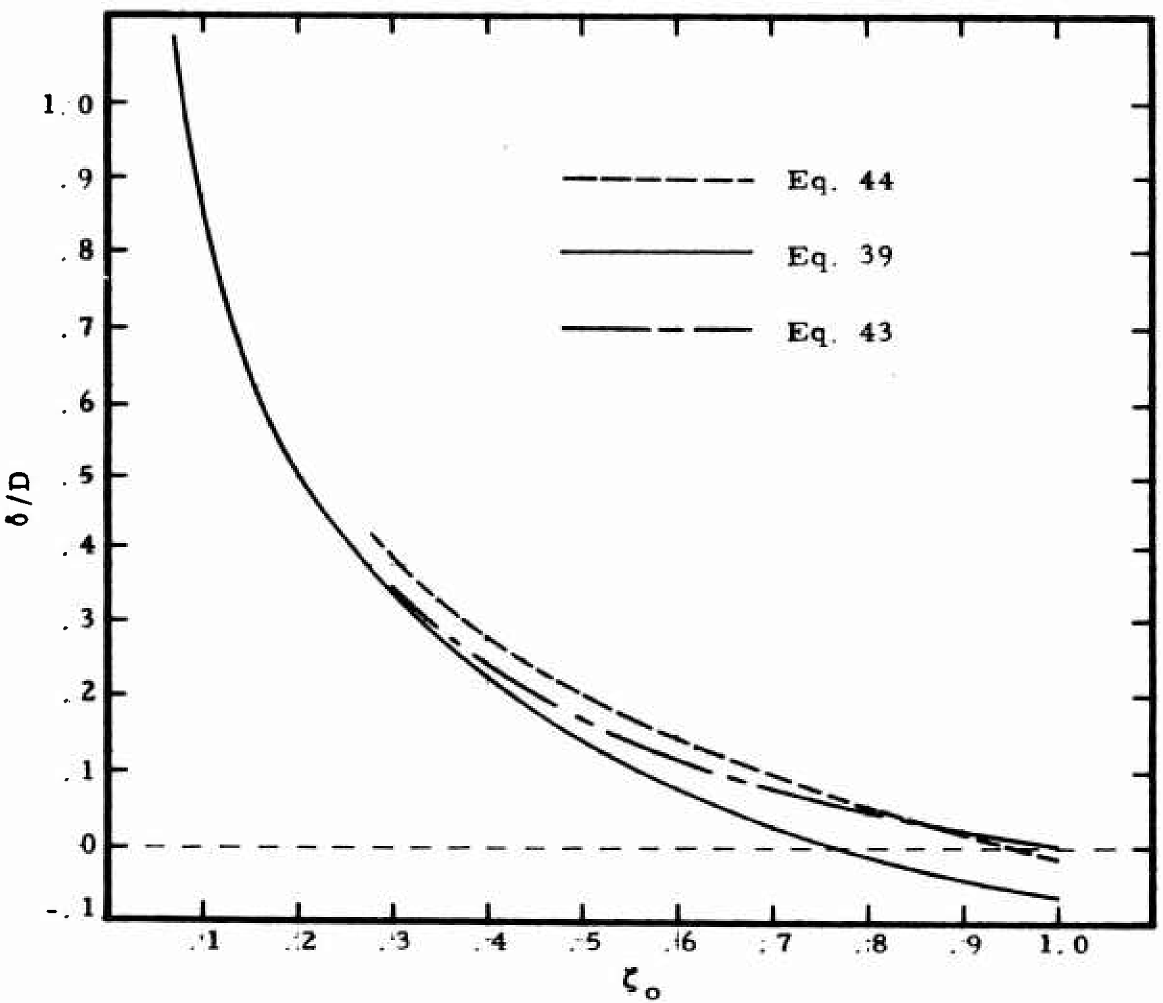

Figure 3. δ/D versus ζ_o

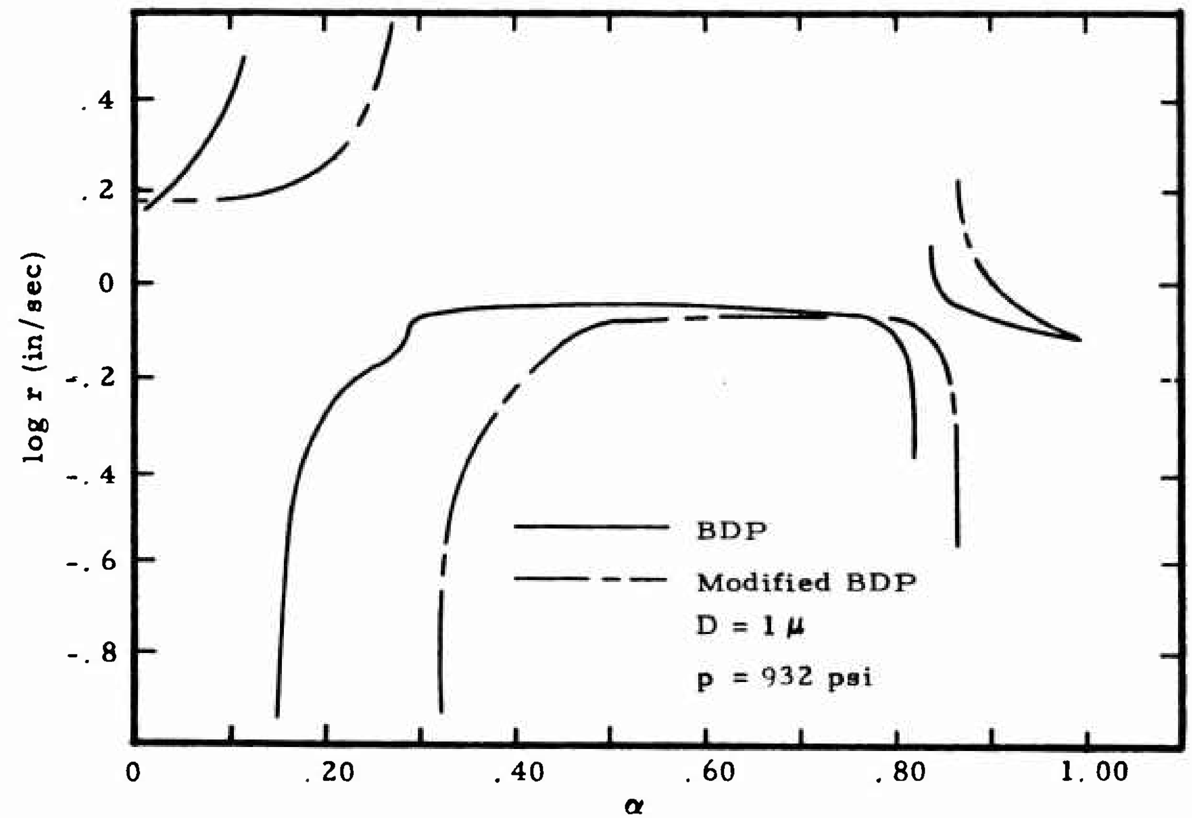

Figure 4. Burning Rate as a Function of Oxidizer Mass Fraction

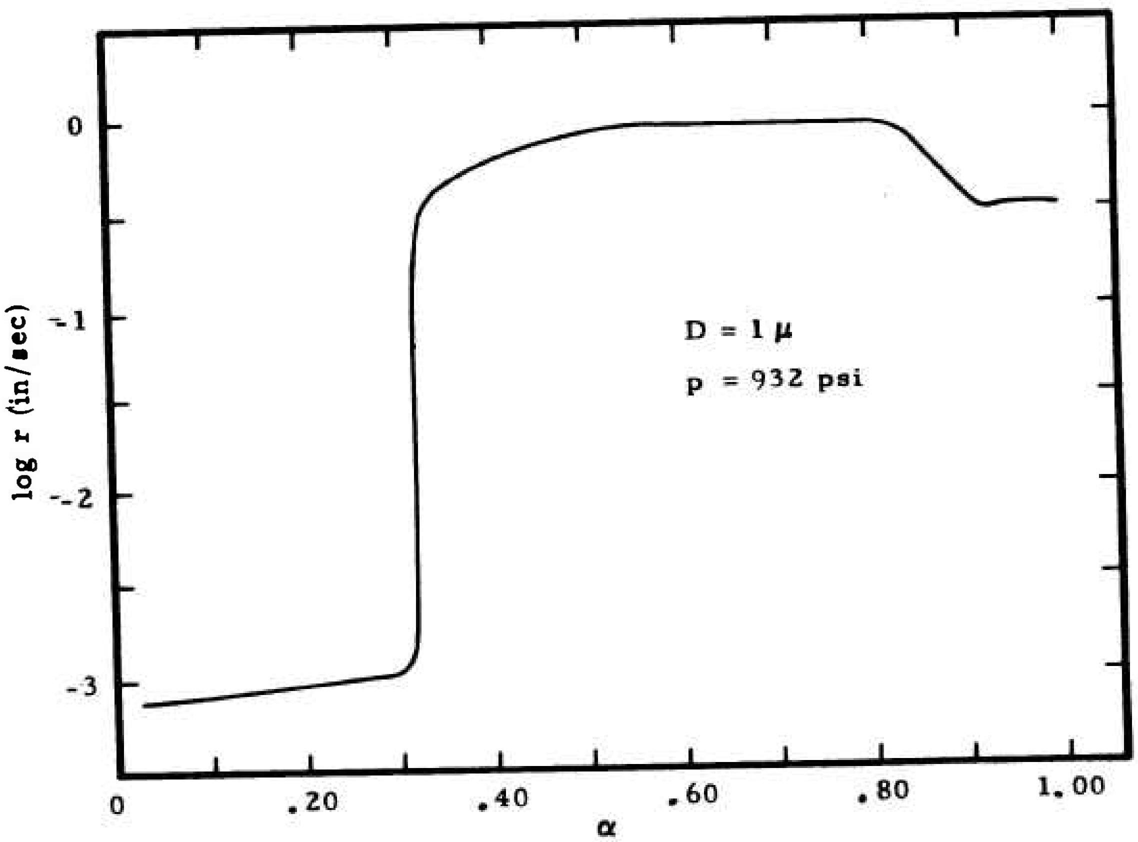

Figure 5. Burning Rate as a Function of Oxidizer Mass Fraction

$$y = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2\right] \quad (45)$$

where

$x = \ln D$

$m = \mathrm{lm}\, \overline{D}_m$

$\sigma = \ln \sigma^*$

This assumption is reasonably realistic and permits each mode to be characterized with minimum input information, thereby assisting parametric studies of particle size effects. Thus, in addition to the standard BDP input parameters, the number of modes, the weight mean diameter and standard deviation of diameter for each mode and the mass fraction of each mode relative to the total mass of oxidizer are needed to characterize the polydisperse oxidizer size distributions in the computer program.

The initial test of the computer program was made with a polydisperse bimodal AP propellant. Oxidizer size distribution data are shown in Table 1. The distributions are depicted in Fig. 6.

TABLE 1

Mode	Mass Fraction of Total Propellant	$\overline{D}$ [μ]	σ^* [μ]
1	0.45	16	2.0
2	0.45	200	1.4

The computer program solves for the mass flux associated with each monodisperse psuedo-propellant in the propellant and sums these fluxes in accordance with Eq. (36) to determine mean propellant burning rate. Figure 7 presents the monodisperse psuedo-propellant burning rates as a function of particle size for several values of n.* Figure 8 illustrates how oxidizer mass fraction varies in the psuedo-propellant family. Viewing Figures 7 and 8 together shows the following:

*Recall that n is an empirical parameter controlling how oxidizer mass fraction varies in the psuedo-propellant family.

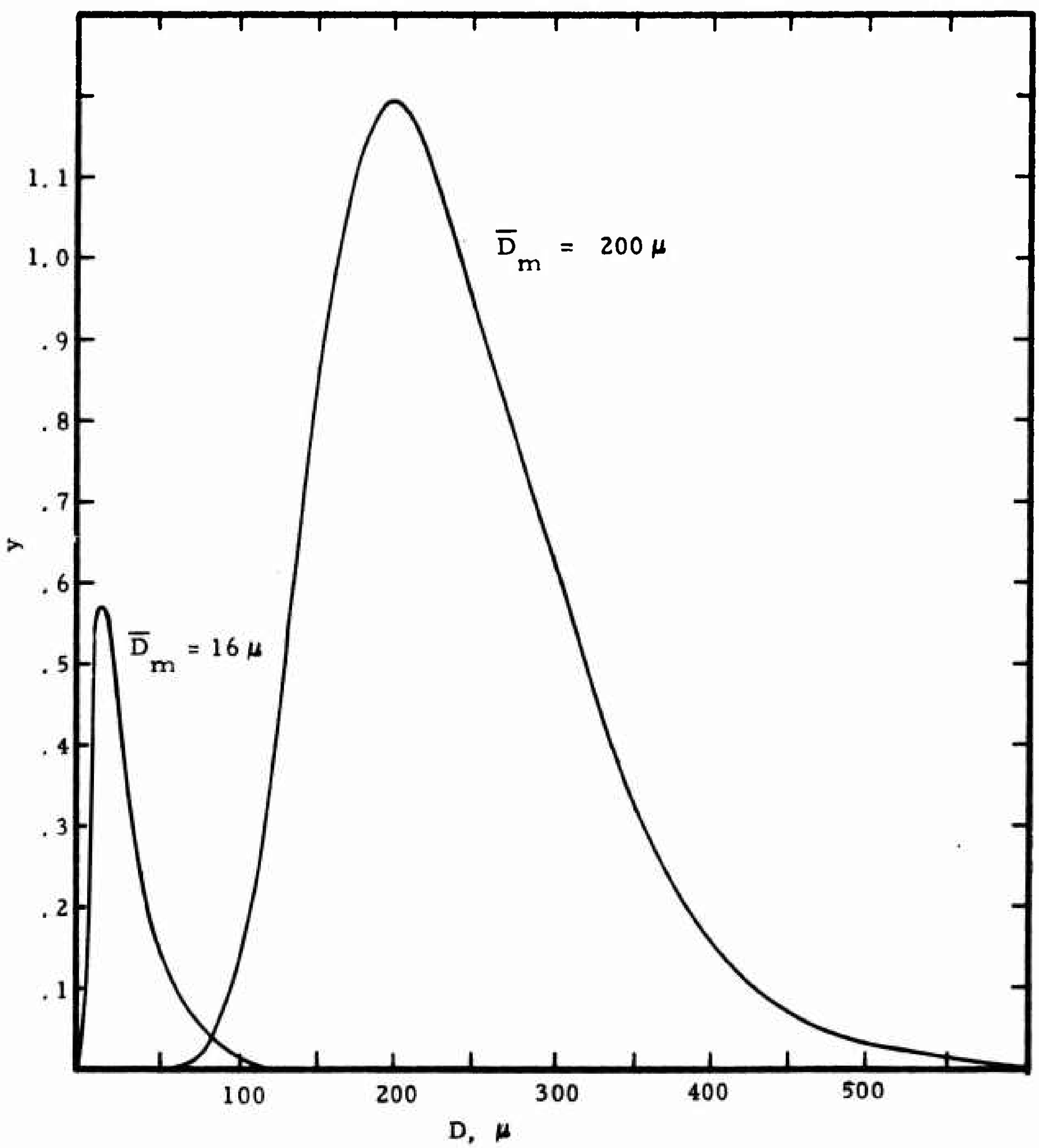

Figure 6. Oxidizer Size Distribution Function

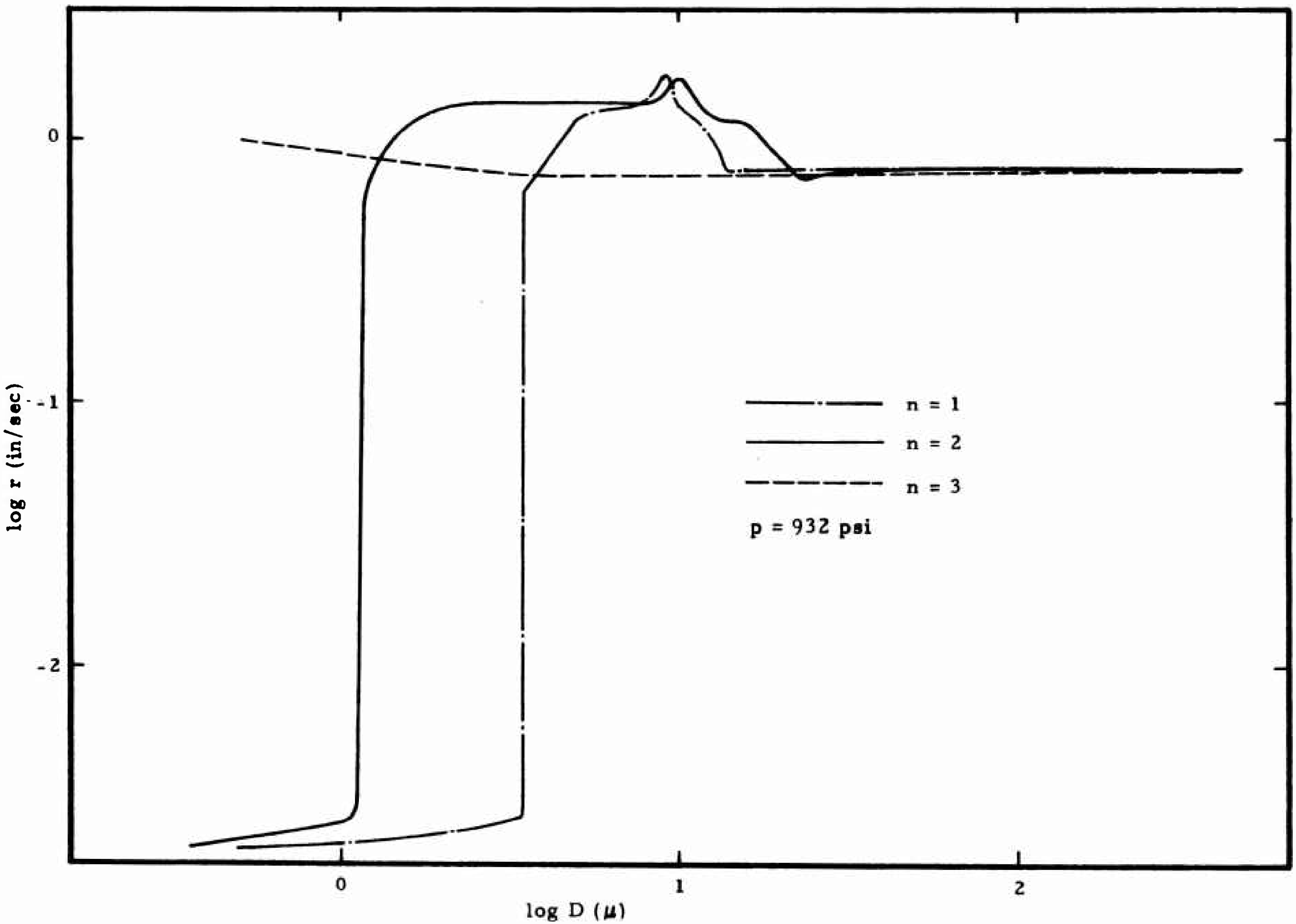

Figure 7. Burning Rate as a Function of Oxidizer Size

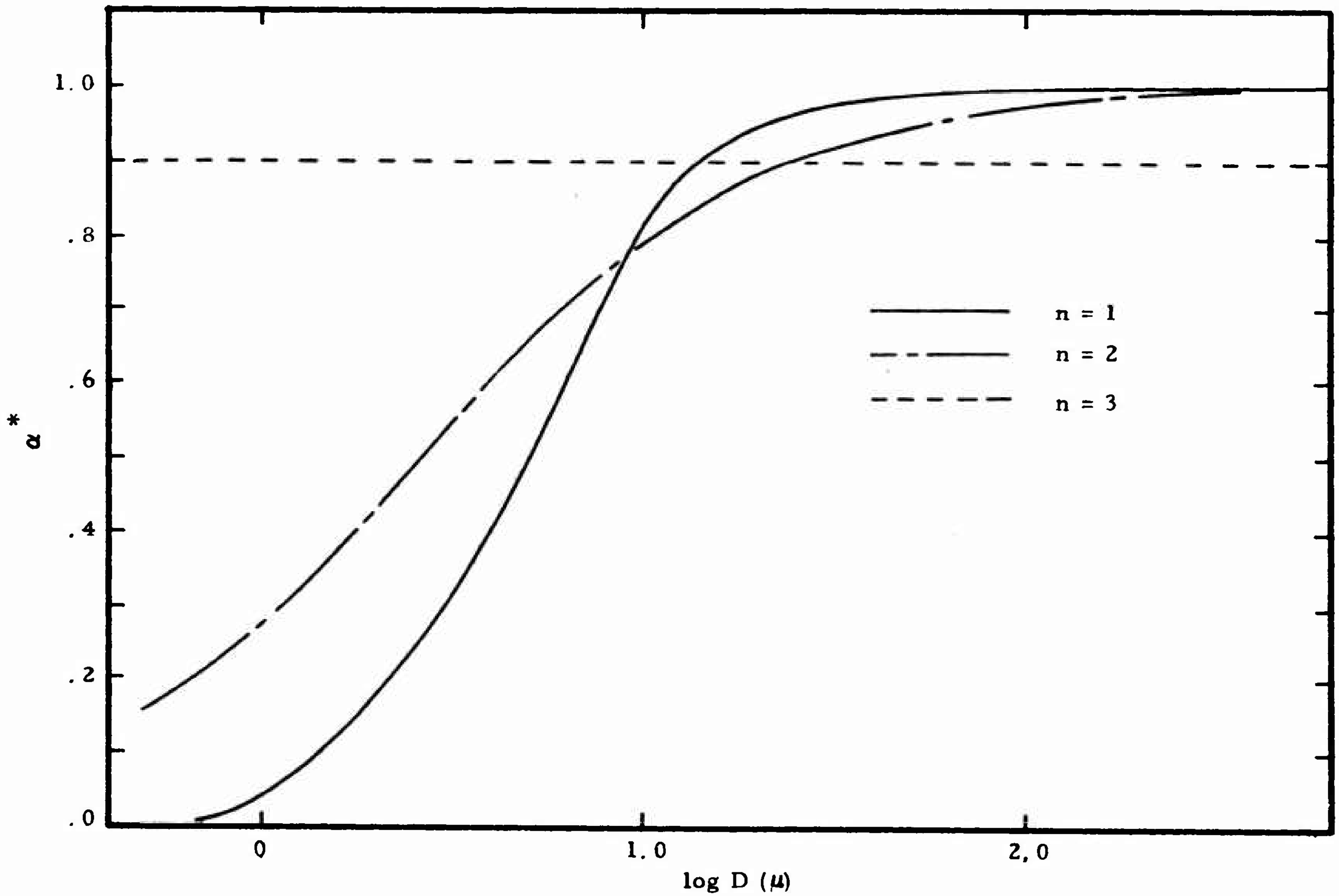

Figure 8. Monodisperse Psuedo-Propellant Mass Fraction as a Function of Oxidizer Particle Size

- o Rate does not vary with particle size by any simple expression reminiscent of the GDF relationship.[14]

- o The way fuel is apportioned among the psuedo-propellants (n) has an enormous effect on the burning rates of the smaller particle sizes.

- o The way fuel is apportioned among the psuedo-propellants (n) has little effect on the burning rates of the larger particle sizes.

The fact that a simple $r \propto D^{-1}$ relationship is not evident suggests that smaller particles do not necessarily augment burning rate by any intrinsically higher rate mechanism. Rather, they appear to partially augment rate by leaning the mixture ratio of the larger particles.

Figure 9 presents the burning rate of the initial case propellant versus pressure. A reasonable exponent is predicted and, somewhat surprisingly, the results are not strongly dependent upon the value of n.

T-BURNER VENT FLOW STUDY

Culick[1][15] has shown, through analysis of the one-dimensional equations of change that a mean flow/acoustics surface interactions term arises naturally in stability analyses. For regions where $d\hat{p}/dz \neq 0$ this term represents a loss of acoustic energy when there is mass addition and a gain of acoustic energy when there is mass subtraction. The latter has led to speculation that the vent of a T-burner yields a gain of acoustic energy for waves in the burner.

However, Culick[15] demonstrates that the adiabatic process leading to a mean flow/acoustic surface interaction <u>loss</u> dissipates acoustic energy into heat. Since acoustic energy is completely available energy, available energy is degraded into heat by this process. Therefore, this process is <u>thermodynamically irreversible</u>. Consequently, the reverse process - the mean flow/acoustics surface interaction <u>gain</u> - is thermodynamically impossible.

This result is almost as surprising as the original mean flow/acoustics surface interaction gain because it contradicts results that arise solely from the equations of change. However, the equations of change do not suffice to define reality because a second law of thermodynamics exists. Therefore, a mean flow/acoustics surface interaction <u>gain</u> process must be a second law violator. Reflection shows that this is the situation because formal reversal of the mean flow/acoustics surface interaction <u>loss</u> implies <u>complete</u> conversion of heat into available energy in an adiabatic process - a phenomena that is disallowed by the second law of thermodynamics.

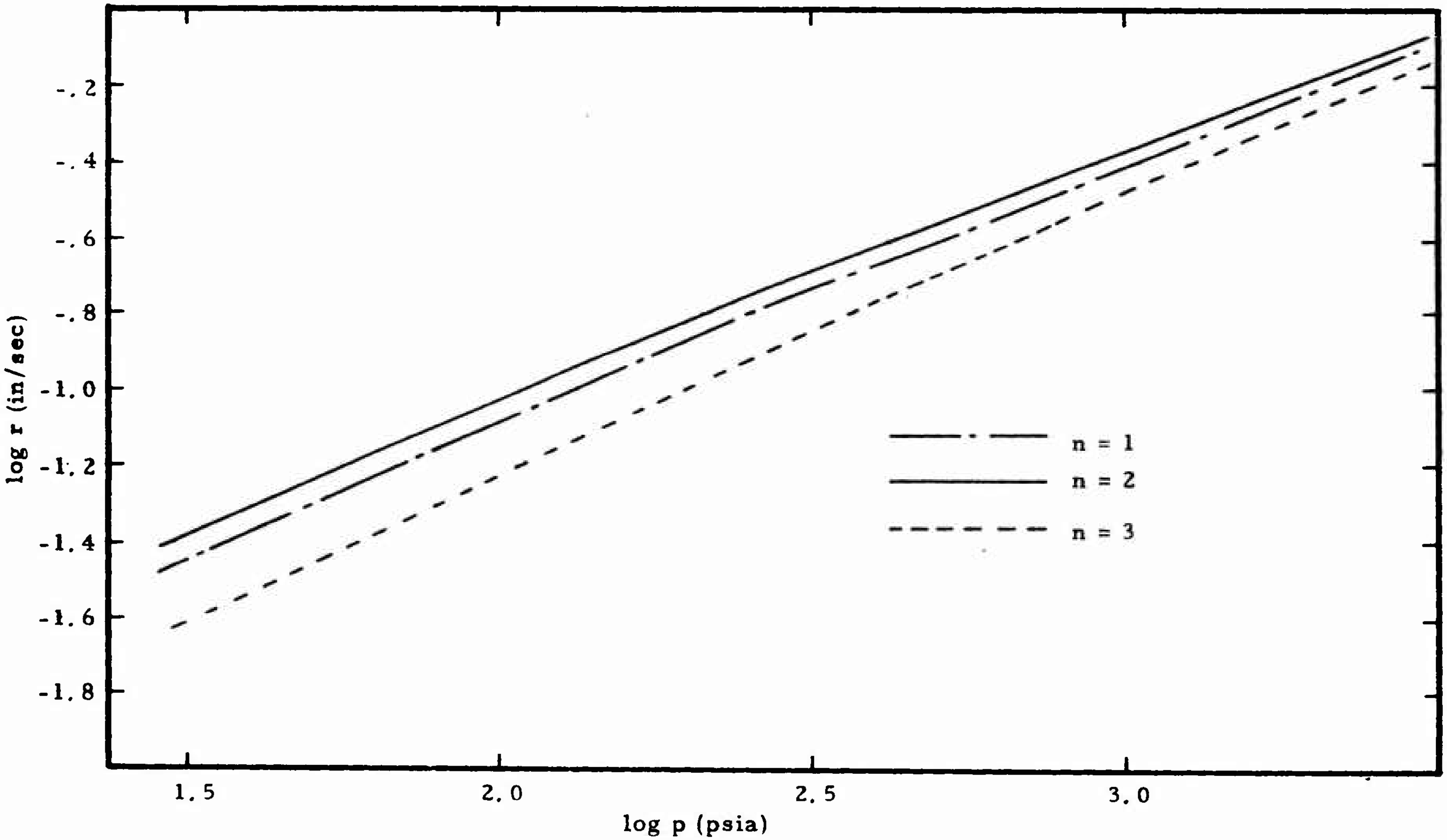

Figure 9. Burning Rate as a Function of Pressure for the Polydisperse Propellant

Why does this result occur and what is the correct result for a mean flow/ acoustic surface interaction when there is mass subtraction? The only "arbitrary" assumption in Culick's analysis is that mass enters and leaves with zero velocity. Is this assumption "legitimate"? Since the one-dimensional equations of change must be valid in the quasi-steady limit, is this assumption "legitimate" in steady-flow? Shapiro[16] shows that it is legitimate for mass addition but violates the second law of thermodynamics for mass subtraction. Moreover, Shapiro shows that the second law requires that mass be rejected with free stream conditions in a steady, one-dimensional flow. Clearly, the mean flow/acoustic surface interactions gain arises from this improper boundary condition. For a proper one-dimensional analysis, Culick's equations must be formulated so they are in harmony with these quasi-steady flow constraints because this is the limit as frequency goes to zero. Culick has also solved this problem[15] and finds in this case that the mean flow/acoustic surface interactions term is zero when there is mass subtraction. Therefore, a properly formulated one-dimensional analysis shows that the vent is neither gain nor loss.

It is important to note that this "new" result is in harmony with physical results. First, atmospheric T-burner test results reported by Horton and Coates[2] demonstrate conclusively that gases at the vent of a T-burner possess axial velocity. Second, hydraulic analogy tests reported by Glick[17] show that in a T-burner with a vent pipe the gases enter the vent with axial momentum and that that axial momentum is transformed in the vent into a Karman vortex sheet. Third, Culick[18] has shown that a flow field like that revealed by the hydraulic analogy studies leads to a vent condition that is neither gain nor loss.

In summary, theoretical and experimental evidence seems to be converging on a null vent condition.

ON REDUCTION OF SOLID ROCKET DATA WHEN THE PRESSURE-TIME HISTORY IS NON-NEUTRAL

Reducing pressure- and thrust-time, propellant mass and web, and nozzle geometry data to determine mean burning rate, mean characteristic velocity, delivered (mean) specific impulse, mean pressure, and mean nozzle geometry is reasonably straightforward with neutral pressure-time histories and minimal nozzle erosion because pressure and nozzle geometry are unique in this situation. However, when the pressure-time history is non-neutral, pressure (and usually nozzle geometry) is no longer unique and choosing the correct mean pressure becomes a problem. It is important to note that functional relationships exist between dependent (r, C^*, I_{sp}) and independent (p, ϵ, etc.) variables. Indeed, one purpose of performance testing is to determine these relationships experimentally. Consequently, when means of dependent variables are defined, means of the independent variables must be derived from these definitions. In other words, when the independent variables (pressure, etc.) vary during a test firing, their means cannot be arbitrarily defined. In Ref. 19 constraints are placed upon independent variable variations during a test. If variations exceed constraints, that data is unacceptable. Although this approach eliminates non-neutral independent variable problems and yields quality performance data, it is not cost effective.

The objectives of this work are twofold. First, to derive general equations defining consistent independent variable means when motor operation is in the quasi-steady regime and pressure and throat area are the independent variables. Second, to obtain first approximation "solutions" to these equations.

Reference 19 defines mean burning rate, mean characteristic velocity, * and delivered specific impulse as

$$\bar{r} = w/t_b \tag{46}$$

$$\bar{C}^* = g \int_{t_I}^{t_I + t_a} A_t \, p \, dt/m_p \tag{47}$$

$$I_{sp,\,d} = \int_{t_I}^{t_I + t_a} F \, dt/m_p \tag{48}$$

*Eq. (47) is a generalization of the more commonly employed $\bar{C}^* = g \, \bar{A}_t \int_{t_I}^{t_I + t_a} p \, dt/m$.

The mean independent variables are defined as*

$$\bar{p}_t = \int_{t_I}^{t_I + t_a} p \; dt / t_a \tag{49}$$

$$\bar{A}_t = \left[A_t (t_I + t_a) + A_t (0) \right] / 2 \tag{50}$$

$$\bar{\epsilon} = A_e (t_I + t_a) / \bar{A}_t \tag{51}$$

Since functionals r (p), C* (p), and I_{sp} (p, ϵ) are presumed to exist, consistent means for p and ϵ require that

$$\bar{r} = r (\bar{p}_r) \tag{52a}$$

$$\bar{C}^* = C^* (\bar{p}_C) \tag{52b}$$

$$I_{sp, d} = I_{sp} (\bar{p}_I, \bar{\epsilon}_I) \tag{52c}$$

where $\bar{p}_r$, $\bar{p}_C$, and $\bar{p}_I$ are mean pressures for burning rate, characteristic velocity, and specific impulse, respectively and $\bar{\epsilon}_I$ is the mean expansion ratio for specific impulses. Since $w = \int_o^{t_b} r (p) \, dt$, Eq. (46) can be written as

*For non-neutral pressure-time histories, Reference 19 suggests that the mass averaged pressure $\bar{p}_m \simeq \int_{t_I}^{t_I + t_a} p^2 \, dt \Big/ \int_{t_I}^{t_I + t_a} p \, dt$ replace the time averaged pressure $\bar{p}_t$.

$$r(\bar{p}_r) = \int_{t_I}^{t_I + t_b} r(p)\,dt \,/\, t_b \tag{53}$$

For quasi-steady conditions $I = \int_{t_I}^{t_I + t_a} I_{sp}\, dm,^{*}$ $m = \int_{t_I}^{t_I + t_a} \dot{m}\, dt$, and $\dot{m} = A_t\, p\, g / C^*$.

Therefore, Eqs. (47) and (48) can be rewritten as

$$C^*(\bar{p}_C) = \int_{t_I}^{t_I + t_a} A_t\, p\, dt \Bigg/ \int_{t_I}^{t_I + t_a} \left[A_t\, p / C^*(p) \right] dt \tag{54}$$

$$I_{sp}(\bar{p}_I, \bar{\epsilon}_I) = g \int_{t_I}^{t_I + t_a} \left[I_{sp}(p, \epsilon)\, A_t\, p / C^*(p) \right] dt \tag{55}$$

Equation (55) does not specify $\bar{p}_I$ and $\bar{\epsilon}_I$ uniquely. Therefore, it is necessary to introduce an arbitrary definition. Since specific impulse and characteristic velocity are both thermodynamic parameters, it is logical that both should possess the same mean pressure. Consequently, assume

$$\bar{p} = \bar{p}_I = \bar{p}_C \tag{56}$$

Examination of Eqs. (53 - 55) shows the following: (a) they are implicit equations; (b) the function desired must be known to determine the desired mean; (c) since r, C^*, and I_{sp} are, in general, neither proportional to p nor independent of p, $\bar{p}_r \neq \bar{p} \neq \bar{p}_m \neq \bar{p}_t$ for non-neutral pressure-time histories; and (d) when the pressure-time history is neutral, $\bar{p}_r = \bar{p} = \bar{p}_m = \bar{p}_t$. Item (b) shows that when the pressure-time history is non-neutral motor test data cannot be reduced on a single firing basis. If the dependent variable is assumed to be an M

*This shows that specific impulse is a mass averaged quantity. Consequently, it has been argued that $\bar{p}_m$ should be employed with $I_{sp,\,d}$ (21), e.g., $\bar{p}_I = \bar{p}_m$. Following this same argument, $\bar{p}_r = \bar{p}_t$.

parameter function of the independent variables, at least M tests are required and data for the M firings must be reduced simultaneously. Items (c) and (d) show that although the CPIA recommendations are exact for neutral pressure-time histories, they are not precisely valid for non-neutral pressure-time histories.

First approximation "solutions" to Eqs. (53 - 56) are obtained by assuming $r = a p^n$, $\bar{C}^*/C^* = 1 + \alpha (p - \bar{p})$, $I_{sp}/I_{sp,d} = 1 + \beta(p - \bar{p}) + \delta(\epsilon - \bar{\epsilon})$.

Then, Eqs. (53 - 56) become*

$$\bar{p}_r = \left(\int_{t_I}^{t_I + t_b} p^n \, dt \Big/ t_b \right)^{1/n} \tag{57}$$

$$\bar{p} = \int_{t_I}^{t_I + t_a} A_t \, p^2 \, dt \Big/ \int_{t_I}^{t_I + t_a} A_t \, p \, dt \tag{58}$$

$$\bar{\epsilon} = \beta(\bar{p}_m - \bar{p})/\delta + A_e \left[\bar{p}_t (1 + \alpha \bar{p}) + \alpha \int_{t_I}^{t_I + t_a} p^2 \, dt \right] \Big/ \int_{t_I}^{t_I + t_a} A_t \, p \, dt \tag{59}$$

If A_t is constant, $\bar{p} = \bar{p}_m$ and $\bar{\epsilon} = A_e/A_t$. Therefore, the CPIA recommendations for non-neutral pressure-time histories are valid as first approximations.

The magnitude of the errors involved with employing $\bar{p}_t$ for $\bar{p}_r$ [Eq. (57)] and $\bar{p}$ [Eq. (58)] can be readily estimated. Expanding the integrands of Eqs. (57) and (58) in a Taylor's series about $p = \bar{p}_t$ gives

$$p^n = \left[1 + n (\Delta p/\bar{p}_t) + n(n-1)(\Delta p/\bar{p}_t)^2/2! + n(n-1)(n-2)(\Delta p/\bar{p}_t^{-3})/3! + \ldots \right] \bar{p}_t^{\,n} \tag{60}$$

*Equation (57) has been obtained previously by Brock.[20]

When $n < 1$, this series has alternating sign. Consequently, when convergent,

$$p^n \simeq [1 + n(\Delta p/\bar{p}_t) + n(n-1)(\Delta p/\bar{p}_t)^2/2!]\,\bar{p}_t^n \tag{61}$$

with error less than $[n(n-1)(n-2)(\Delta p/\bar{p}_t)^3/3!]$.[21] Substitution of Eq. (61) into Eq. (57), integrating, and applying the mean value theorem for integrals gives

$$\bar{p}_r \simeq \bar{p}_t \left[1 + n(n-1)\overline{\left[(\Delta p/\bar{p}_t)^2\right]}/2\right]^{1/n} \tag{62}$$

Substitution of Eq. (61) with $n = 2$ into Eq. (58), assuming A_t is constant, integrating, and applying the mean value theorem for integrals gives

$$\bar{p} = \bar{p}_t \left\{1 + \overline{\left[(\Delta p/\bar{p}_t)^2\right]}\right\} \tag{63}$$

Examination of Eqs. (62) and (63) shows that when $\Delta p/\bar{p}_t$ is small, $\bar{p}_r$ and $\bar{p}$ agree with $\bar{p}_t$ to first order accuracy. However, when $\Delta p/\bar{p}_t$ is large, significant deviations can occur. Calculations presented by Brock[20] support this.

In summary, this work has shown that consistent reduction of motor test data when the pressure-time history is non-neutral falls outside conventional procedure. As long as deviations from neutrality are small, errors relative to established procedure are small. However, when deviations become large, significant errors can result. This work has assumed that motor operations falls in the quasi-steady regime and that pressure and throat area are the only independent variables. However, burning rate depends on flow over the burning surface and the thermodynamic parameters depend at least upon stay time and nozzle geometry. Therefore, what has been presented here is just a ripple on the surface of the basic problem of extracting all possible truth from available data.

FUTURE PLANS

Future efforts will be expended in four directions:

- modification of the BDP combustion model
- generation and implementation of propellant burning rate computer codes
- consideration of transient burning phases within the steady-state statistical framework
- application of the hydraulic analogy to determine mean flow effects on mode shape.

In the first, extension of the model to include spheriodal particles and surface tension effects will be explored. In the second, computer codes for predicting burning rates in additive free propellants will be developed. In the third, basic problems in statistical combustion modeling will be explored. Specifically, transient effects and statistical formulations with nonplanar burning surfaces will be pursued. In the latter, hydraulic analogy test sequences with real motor geometry and distributed mass addition will be employed to assess mode shape deviations wrought by mean flow effects. This will be accomplished by determining the resonant frequencv and then measuring amplitude and phase along the motor length (light absorption technique). Comparison of results at no flow with acoustic approximation results "defines" analogy errors; comparison of analogy results at various port Mach numbers "indicates" mean flow errors.

PUBLICATIONS DERIVED FROM PROGRAM

1. On Reduction of Solid Rocket Data When the Pressure-Time History is Non-Neutral, accepted for publication, Journal Spacecraft and Rockets, 1975.

2. Hydraulic Analogy Study: T-Burner Vent Gain/Loss, CPIA Publication No. 261, Vol. 1, 1974, pp. 491-498.

3. Comment on "The Stability of One-Dimensional Motions in a Rocket Motor", accepted for publication, Combustion Science and Technology, 1975.

NOMENCLATURE

Latin Symbols

A_e	nozzle exit area
A_t	nozzle throat area
b	$\bar{D}$ + ^
C	constant defined by Eq. (19)
C^*	characteristic velocity
D	diameter
F	distribution function
g	gravitational acceleration
h	water depth
I	delivered impulse
I_{sp}	specific impulse
$I_{sp,d}$	delivered specific impulse
m	mass
$\dot{m}$	mass flow rate
m''	mass flux
M_k	number of modes associated with k^{th} oxidizer species
n	exponent defined by Eq. (19)
p	pressure
Q	number of subdivisions
r	burning rate
s	number of oxidizer species
S	surface area

t	time
t_a	action time
t_b	burn time
t_I	time when p first becomes $0.05\,\bar{p}_t$
u	velocity component in x direction
v	velocity component in y direction
V	volume
w	propellant web or velocity component in z direction
x, y, z	coordinates in inertial reference frame
y	$dm_{o,j,k} / (m_{o,j,k}\, dD)$
z	distance normal to S

Greek Symbols

α	mass oxidizer/mass propellant
ζ	volume oxidizer/volume propellant
δ	width of fuel annulus surrounding mean oxidizer particle
Δ	denotes a small quantity
$\eta_{d,k}$	fraction of oxidizer particles on burning surface with $D \le D \le D + dD$ and species k
ϵ	nozzle expansion ratio
σ^*	standard deviation of oxidizer particle size distribution
ρ	density

Special Symbols

$\overline{(\ )}$	denotes a mean
$(\ )^*$	pertains to a monodisperse, psuedo-propellant
$\hat{(\ )}$	denotes a fluctuating term such that $\overline{\hat{(\ )}} = 0$
$(\ )^+$	denotes a non-dimensional quantity

Subscripts

b	denotes burning surface
d	denotes oxidizer particles with $D \leq D \leq D + dD$
f	denotes fuel
g	denotes gas
j	denotes oxidizer mode j
k	denotes oxidizer species k
m	denotes weight mean in oxidizer particle size distribution
o	denotes oxidizer or stagnation condition
t	denotes time mean or propellant
p	denotes planar surface
v	denotes per unit volume
w	denotes water

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APPENDIX A

COMPUTER PROGRAM

COMPUTER PROGRAM DATA INPUT FORMAT

CARD 1: Control Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify run options

FORMAT: (2I6)

Columns 1-6: NJOB, if NJOB = 1 read propellant parameters, if NOB = 2 read namelist data

Columns 7-12: IPLOT, IPLOT = 2, (Plotting routine presently deleted)

CARD 2: Title Card

NUMBER REQUIRED: One card per run

FUNCTION: Identify run out at

FORMAT: (20A4)

Columns 2-80: May be used to identify run

CARD 3: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: TZERO, initial propellant temperature, deg K

Columns 13-24: ALFA, Oxidizer mass fraction

Columns 25-36: TF, adiabatic flame temperature, deg K

Columns 37-48: GMW, molecular weight of final flame

Columns 49-60: XNUI, stoichiometric ratio of the final flame

Columns 61-80: not used

CARD 4: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: QFUEL, heat of pyrolysis of the fuel binder, cal/g

Columns 13-24: RHOF, density of fuel binder, g/cm^3

Columns 25-36: AF, arrhenius frequency factor of fuel binder, g/cm^2-sec

Columns 37-48: EF, activation energy of the fuel binder, cal/mole

Columns 49-60: XNUP, primary flame stoichiometric ratio

Columns 61-72: PMW, primary flame molecular weight

Columns 73-80: not used

CARD 5: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: QL, latent heat of vaporization of the oxidizer, cal/g

Columns 13-24: RHOX, density of the oxidizer, g/cm^3

Columns 25-36: AOX, arrhenius frequency factor of the oxidizer g/cm^2-sec

Columns 37-48: EOX, activation energy of the oxidizer cal/mole

Columns 49-60: TAP, temperature of the AP flame, deg K

Columns 61-72: AP, AP=1 if oxidizer rate constants specified, AP = -1 or 0 if oxidizer rate constant to be calculated by program. If -1, mass flux of oxidizer taken as 1.9 g/cm^2-sec in rate constant calculation. If 0, mass flux of oxidizer taken as 1.66 g/cm^2-sec in rate constant calculation.

Columns 73-80: not used

CARD 6: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: CIGN, oxidizer ignition delay parameter, $sec(atm)^m$ cm^{-n+1} where m=POWIGN and n=POWD

Columns 13-24: POWIGN, pressure exponent in oxidizer particle ignition particle ignition delay term

Columns 25-36: POWD, diameter exponent in oxidizer particle ignition delay term

Columns 37-48: PSTART, pressure to start incremental calculations, atm

Columns 49-60: PSTOP, pressure to stop incremental calculations, atm

Columns 60-72: CONF, CONF=0 if parabolic flame assumed, CONF=1 if conical flame assumed

Columns 73-80: not used

CARD 7: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: KPF, rate constant of primary flame, g/cm^3-sec-atm)

Columns 13-24: KAP1, rate constant of AP flame at low pressure, g/(cm^3-sec-atm)

Columns 25-36: KAP2, rate constant of AP flame at high pressure, g/cm^3-sec-atm)

Columns 37-48: XN1, reaction order of primary flame

Columns 49-60: XN2, reaction order of AP flame at low pressure

Columns 61-72: XN3, reaction order of AP flame at high pressure

Columns 72-80: not used

CARD 8: Data Card

NUMBER REQUIRED: One card per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: CSUBP, average heat capacity of solids and gases, cal/g-^{o}K

Columns 13-24: XLAMB, average thermal conductivity of the combustion gases, cal/cm-sec-^{o}K

Columns 25-36: GAMMA, diffusion parameter, cm^2/sec

Columns 37-48: AFH, flame height factor

Columns 49-60: EPS, exponent for diffusion pressure dependence

Columns 61-72: Y, proportionality constant for short diffusion flame

Columns 72-80: not used

CARD 9: Data Card

NUMBER REQUIRED: One per run

FUNCTION: Specify propellant parameters

FORMAT: (6E12.6)

Columns 1-12: BETA, mass fraction of metal

Columns 13-24: RHOM, density of metal, g/cm^3

Columns 25-36: QM, heat release of metal combustion, cal/g

Columns 37-80: not used

CARD 10: Data Card

NUMBER REQUIRED: One per case

FUNCTION: Specify integration parameters

FORMAT: (3I5, 3F10.5)

Columns 1-5: NMODES, number of oxidizer size distribution modes

Columns 6-10: NCOUNT, number of intervals in the numerical integration of total propellant mass flux

Columns 10-15: NXCOUN, number of intervals in the numerical integration for the proportionality constant C in the equation for the volume of fuel associated with a particle in a polydisperse packing

Columns 16-25: XN, diameter exponent in the equation for the volume of fuel associated with a particle in a polydisperse packing.

Columns 26-35: DDO, oxidizer particle size increment in the numerical integration of total propellant mass flux.

Columns 36-45: XDDO, oxidizer particle size increment in the numerical integration for the proportionality constant C

CARDS 10 to 11 +NMODES: Data Card

NUMBER REQUIRED: One per oxidizer mode size, per case

FUNCTION: Specify oxidizer size distribution parameters

FORMAT: (3F10.5)

Columns 1-10: SIGMA, standard deviation of oxidizer size distribution for a particular mode

Columns 11-20: DBAR, mean oxidizer crystal size for a particular mode, microns

Columns 21-30: YI, mass fraction of oxidizer in a particular mode relative to the total mass of oxidizer.

Columns 31-80: not used

CARD 11 +NMODES: Control Card

NUMBER REQUIRED: One card per case

FUNCTION: Start next case or terminate run

FORMAT: (I4)

Columns (1-4): NSTOP, if NSTOP >1 terminate program, if NSTOP ≤ 1 begin next case

CARD 12 + NMODES: Data Card

NUMBER REQUIRED: One card per additional case

FUNCTION: Specify propellant parameters

FORMAT: NAMELIST/NAM1/

REMARKS: Used only when more than one case is run.

CARD 13 + NMODES: Data Card

NUMBER REQUIRED: One card per additional case

FUNCTION: See Card 10

FORMAT: See Card 10

CARD 13 + $NMODES_{case\ one}$ to (12 + $NMODES_{case\ one}$ + $NMODES_{case\ two}$): Data Card

NUMBER REQUIRED: One per mode in case two

FUNCTION: See Cards 11 to 10+$NMODES_{case\ one}$

FORMAT: See Cards 11 to 10+$NMODES_{case\ one}$

CARD 13 + $NMODES_{case\ one}$ + $NMODES_{case\ two}$: Control Card

NUMBER REQUIRED: One per additional case

FUNCTION: See Card 11 + $NMODES_{case\ one}$

FORMAT: See Card 11 + $NMODES_{case\ one}$

COMPUTER PROGRAM LISTING

AND

SAMPLE CALCULATION

```
               C
0001                 IMPLICIT REAL*8 (A-H,O-Z)
0002                 REAL*8 KAP1,KAP2,KPF,MOX,MT
0003                 COMMON A1,        A2,       AF,       AFH,      ALFAST,   ANSI(50),469 0004
                    1      ADX,        BESS,     BESSI(50),BETAF,    BSQR,              469 0005
                    2                  CIGN,     CON1,     CSUBP,    DELDI,    DZERO,   469 0006
                    3      EF,         ECX,      ETA,      GAMMA,    GMW,      HDN,     469 0007
                    4      HDP,                                      KAP1,     KAP2,
                    5      KPF,                  MOX,      MT,                 P,
                    6      POWD,       POWIGN,   PSTART,   PSTOP,    QAP,      QFF      469 0010
0004                 COMMON QFUEL,     QL,       QPF,      R,        RAP,      RF,      469 0011
                    1      RHOF,       RHOSP,    RHOX,     RON,      SOX,      TAP,     469 0012
                    2      TAV,        TF,       TIT(20),  TIT1(20), TZERO,             469 0013
                    3      XLAMB,      XN1,      XN2,      XN3,      XNUST,    XNU1     469 0014
0005                 COMMON XNUP, XALFA, PMW, ETAP, EPS
0006                 COMMON/DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
0007                 COMMON/XINT/ IJIM, IPLOT, K, MEM1, NP1
0008                 COMMON/XRAT/ RHOP,BR
0009                 DIMENSION XMT(100), FZERO(100), XXNU(100), D(100)
0010                 CALL ZEROSC(A1,EPS)
0011                 A1 = 0.5D0*(1.0D0 + 1.0D0/DSQRT(3.0D0))
0012                 A2 = 0.5D0*(1.0D0 - 1.0D0/DSQRT(3.0D0))
0013                 CALL INPUT(0)                                                  469 0022
0014                 CALL INPUT1 (JJ,0,D,FZERO,XNU,NCOUNT,DDD)
0015               2 CALL CONCAL (0)                                                469 0023
0016                 TS = 750.0D0
0017                 K = 1                                                          469 0024
0018                 R = .06D0*DSQRT(P)
0019                 SOX = XNU                                                      469 0026
0020                 WRITE(6,5001)
0021                 GO TO 9
0022              25 WRITE(6,5001)
0023              22 CALL INPUT1 (JJ,2,D,FZERO,XNU,NCOUNT,DDD)
0024               9 CALL STEMP                                                     469 0027
0025                 XSPF = XSTPF*10000.0D0
0026                 XSPD = XSTPD*10000.0D0
0027                 XSD = XSTARD*10000.0D0
0028                 XSAP = XSTAP*10000.0D0
0029                 WRITE(6,5000) JJ,R,FZERO(JJ),DZERO,XSPF,XSAP,XSPD,XSD,ALFAST,XNUST
0030            5000 FORMAT(6X,I6,4X,2F12.4,F12.1,4F12.2,2F12.4)
0031                 CALL XSTOR (JJ,XMT,XNUST,XNU,MT,XXNU)
0032                 IF (NCOUNT - JJ) 23, 22, 22
0033              23 CALL FINRAT (XMT,D,FZERO,DDD,XXNU,NCOUNT)
0034                 JJ = 1
0035                 R = BR
0036                 CALL OUTPUT (1)                                                469 0028
0037                 IF (P - PSTOP) 31, 32, 32                                      469 0029
0038              31 CALL CONCAL (1)                                                469 0030
0039                 GO TO 25
               C     THIS PRINTS THE HEADER INFORMATION AFTER THE CALCULATIONS      469 0032
               C     HAVE BEEN MADE                                                 469 0033
0040              32 CALL OUTPUT(2)                                                 469 0034
0041                 READ(5,103) NSTOP
0042                 IF(NSTOP.GE.1) GO TO 50
0043                 CALL INPUT (1)                                                 469 0035
0044                 GO TO 2                                                        469 0036
0045             100 FORMAT (I4)                                                    469 0037
0046             102 FORMAT (2E12.6)                                                469 0038
0047             103 FORMAT(I5)
0048            5001 FORMAT(1H1,9X,2HJJ,11X,1HR,8X,6HFZEROP,4X,5HDZERO,12X,5HXSTPF,7X,5
                    1HXSTAP,5X,5HXSTPD,7X,6HXSTARD,7X,6HALFAST,6X,5HXNUST//)
0049              50 STOP
0050                 END                                                            469 0039
```

```
              C      ******                      CONCAL                ******
0001                 SUBROUTINE CONCAL (J)                                      469 0040
0002                 IMPLICIT REAL*8 (A-H,O-Z)
              C      THIS SUBROUTINE INCREMENTS THE PRESSURE                    469 0041
0003                 DIMENSION FAC(10)                                          469 0042
0004                 REAL*8 KAP1, KAP2, KPF, MOX, MT
0005                 COMMON A1,       A2,       AF,       AFH,      ALFAST,   ANSI(50),469 0004
                    1       AOX,      BESS,     BESSI(50),BETAF,    BSQR,              469 0045
                    2                 CIGN,     CON1,     CSUBP,    DELDI,    DZERO,   469 0046
                    3       EF,       EOX,      ETA,      GAMMA,    GMW,      HDN,     469 0047
                    4       HDP,                                    KAP1,     KAP2,
                    5       KPF,                MOX,      MT,                 P,
                    6       POWD,     POWIGN,   PSTART,   PSTOP,    QAP,      QFF      469 0050
0006                 COMMON QFUEL,    QL,       QPF,      R,        RAP,      RF,      469 0051
                    1       RHOF,     RHOSP,    RHOX,     RON,      SOX,      TAP,     469 0012
                    2       TAV,      TF,       TIT(20),  TIT1(20), TZERO,             469 0053
                    3       XLAMB,    XN1,      XN2,      XN3,      XNUST,    XNU1     469 0014
0007                 COMMON XNUP, XALFA, PMW, ETAP, EPS
0008                 COMMON/DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
0009                 COMMON/XINT/ IJIM, IPLOT, K, MEM1, NP1
0010               1 IF (J) 2, 2, 15                                            469 0057
0011               2 FAC(1)=1.0
0012                 FAC(2)=1.77
0013                 FAC(3)=3.17
0014                 FAC(4)=5.62
0015                 FAC(5)=10.0
0016                 JJ = 0                                                     469 0068
0017                 I = 1                                                      469 0069
0018              15 IF (JJ - 1) 16, 20, 20                                     469 0070
0019              16 XMULT = PSTART                                             469 0071
0020                 JJ = 1                                                     469 0072
0021                 I = 1                                                      469 0073
0022              20 IF (I-6) 50,21,21
0023              21 XMULT = XMULT*10.                                          469 0075
0024                 I = 2                                                      469 0076
0025              50 P = XMULT*FAC(I)                                           469 0077
0026                 I = I + 1                                                  469 0078
0027                 RETURN                                                     469 0079
0028                 END                                                        469 0080
```

```
            C       ******                     STEMP                         ******
0001                SUBROUTINE STEMP                                                    469 0081
0002                IMPLICIT REAL*8 (A-H,O-Z)
0003                EXTERNAL DON                                                        469 0082
0004                REAL*8 KAP1, KAP2, KPF, MOX, MT
0005                COMMON A1,       A2,       AF,        AFH,      ALFAST,   ANSI(50),469 0004
                   1      ADX,       BESS,     BESSI(50),BETAF,    BSQR,               469 0085
                   2                 CIGN,     CON1,      CSUBP,    DELDI,    DZERO,    469 0086
                   3      EF,        EOX,      ETA,       GAMMA,    GMW,      HDN,      469 0087
                   4      HDP,                                      KAP1,     KAP2,
                   5      KPF,                 MOX,       MT,                 P,
                   6      POWD,      POWIGN,   PSTART,    PSTOP,    QAP,      QFF       469 0090
0006                COMMON QFUEL,    QL,       QPF,       R,        RAP,      RF,       469 0091
                   1      RHOF,      RHOSP,    RHOX,      RON,      SOX,      TAP,      469 0012
                   2      TAV,       TF,       TIT(20),   TIT1(20), TZERO,              469 0093
                   3      XLAMB,     XN1,      XN2,       XN3,      XNUST,    XNU1      469 0014
0007                COMMON XNUP, XALFA, PMW, ETAP, EPS
0008                COMMON/DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
0009                COMMON/XINT/ IJIM, IPLOT, K, MEM1, NP1
0010                COMMON/ETAY/ Y
0011                DIMENSION ARGLST(20),AN(5)                                          469 0097
0012                ALFA = ALFAST
0013                XNU = XNUST
0014                XNU2 = (1.0D0 - ALFAST)*XNU1/ALFAST
0015                XNUQ = (1.0D0 - ALFAST)*XNUP/ALFAST
0016                RHOP = RHOSP
0017                BSQR = (DZERO**2/6.0D0)*(1.0D0/XNU) *1.0D-08
0018                DELDI = (1.0D0/(DSQRT(XNU)) - 1.0D0)*(1.0D0/(DSQRT(6.0D0)))
0019                CON1 = DSQRT(XNU)
0020                ARG = 3.83D0*CON1
0021                CALL BESSEL (0.0, ARG, AN)                                          469 0185
0022                BESS = AN(3)                                                        469 0186
0023                DUM1 = 3.215D0*CON1*(1.0D0 + XNU2)*BESS/(XNU2 - (1.0D0 + XNU2)*CON
                  11**2)
0024                IF (DUM1) 40, 40, 41
0025            41  ETA = DLOG (DUM1)
0026                GO TO 42
0027            40  ETA =  DLOG (-1.293D0*DUM1/3.215D0)
0028            42  DUM1 = -1.293D0*CON1*(1.0D0 + XNUQ)*BESS/(XNUQ - (1.0D0 + XNUQ)*CO
                  1N1**2)
0029                IF (DUM1) 20, 20, 21
0030            20  ETAP =  DLOG (3.215D0*DUM1/(-1.293D0))
0031                GO TO 22
0032            21  ETAP = DLOG (DUM1)
0033            22  QFF = CSUBP*((TF - 298.0D0) - ALFA*(TAP - 298.0D0) + (1.0D0 - ALFA
                  1 )/CSUBP*QFUEL)/ALFA
0034                QPF = CSUBP*((TF - 298.0D0) + ALFA*QL/CSUBP + (1.0D0 - ALFA ) *
                  1 QFUEL/CSUBP)
0035                QAP = CSUBP*(TAP - 298.0D0) + QL
0036                ETA = Y/ETA
0037                ETAP = Y/ETAP
0038                CON2 = GAMMA*TAV**0.75D0/82.06D0*GMW
0039                C3 = 2.0D0*CON2*ETA*AFH
0040                C4 = (7.66D0*CON2)**2/BSQR
0041            32  XNC = XN2                                                           469 0101
0042                RATC = KAP1                                                         469 0102
0043                MT = RHOP*R                                                         469 0103
0044                XMT = 0.0D0                                                         469 0104
```

```
            C      ******                  INPUT                      ******
0001               SUBROUTINE INPUT (M1)                                       469 0133
0002               IMPLICIT REAL*8 (A-H,O-Z)
0003               REAL*8 KAP1, KAP2, KPF, MOX, MT
0004               REAL*8 MOX70
0005               COMMON A1,        A2,       AF,        AFH,       ALFAST,    ANSI(50),469 0004
                  1       ADX,       BESS,     BESSI(50),BETAF,     BSQR,               469 0136
                  2                  CIGN,     CON1,      CSUBP,     DELDI,     DZERO,   469 0137
                  3       EF,        EOX,      ETA,       GAMMA,     GMW,       HDN,     469 0138
                  4       HDP,                                       KAP1,      KAP2,
                  5       KPF,                 MOX,       MT,                   P,
                  6       POWD,      POWIGN,   PSTART,    PSTOP,     QAP,       QFF      469 0141
0006               COMMON QFUEL,     QL,       QPF,       R,         RAP,       RF,      469 0142
                  1       RHOF,      RHCSP,    RHCX,      RON,       SOX,       TAP,     469 0012
                  2       TAV,       TF,       TIT(20),   TIT1(20),  TZERO,              469 0144
                  3       XLAMB,     XN1,      XN2,       XN3,       XNUST,     XNU1     469 0014
0007               COMMON XNUP, XALFA, PMW, ETAP, EPS
0008               COMMON /PBC/ CONF                                                   469 0148
0009               COMMON /RWN/ BETA, RHOM, QM                                         469 0149
0010               COMMON/DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
0011               COMMON/XINT/ IJIM, IPLOT, K, MEM1, NP1
0012               COMMON/ETAY/ Y
0013               DIMENSION AN(4)                                                     469 0151
0014               NAMELIST /NAM1/ IPLOT, NJOB, ITIT, TZERO, ALFA, TF, GMW, XNU1,      469 0152
                  1 DZERO, QFUEL, RHOF, AF, EF, XNUP, PMW, QL, RHOX, ADX, EOX, TAP,   469 0153
                  1 AP, CIGN, POWIGN, POWD, PSTART, PSTOP, CONF, KPF, KAP1, KAP2,     469 0154
                  1 XN1, XN2, XN3, CSUBP, XLAMB, GAMMA, AFH, EPS, Y, BETA, RHOM, QM   469 0155
0015               DATA NJOB/1/                                                        469 0156
0016               GO TO (1, 2), NJOB                                                  469 0157
0017             1 READ (5,800) NJOB, IPLOT                                            469 0158
0018               READ (5,801) (TIT1(I7), I7=1,8)                                     469 0159
0019               READ (5,802) TZERO, XALFA, TF, GMW, XNU1, XDZERO
0020               READ (5,802) QFUEL, RHOF, AF, EF, XNUP, PMW                         469 0161
0021               READ (5,802) QL, RHOX, ADX, EOX, TAP, AP                            469 0162
0022               READ (5,802) CIGN, POWIGN, POWD, PSTART, PSTOP, CONF                469 0163
0023               READ (5,802) KPF, KAP1, KAP2, XN1, XN2, XN3                         469 0164
0024               READ (5,802) CSUBP, XLAMB, GAMMA, AFH, EPS, Y                       469 0165
0025               READ (5,902) BETA, RHOM, QM                                         469 0166
0026               NJOB = 2                                                            469 0167
0027               GO TO 10                                                            469 0168
0028             2 READ (5,NAM1)                                                       469 0169
0029               IF (NJOB - 2) 3, 3, 11                                              469 0170
0030             3 CONTINUE
0031             4 CONTINUE
0032            10 CONTINUE
0033            11 CONTINUE
0034               ITIT = 0                                                            469 0179
0035               IF (AP) 22, 21, 20                                                  469 0204
            C      CALCULATE OXIDIZER RATE CONSTANT, AS NONE WAS GIVEN                469 0205
0036            22 MOX70 = 1.9D0
0037               GO TO 23                                                            469 0207
0038            21 MOX70 = 1.66D0                                                      469 0208
0039            23 TS70 = -EOX/(1.987D0* DLOG(MOX70/ADX))
0040               ZS70 =  DLOG ((TAP + QL/CSUBP - 298.0D0)/(QL/CSUBP - 298.0D0 +
                  1 TS70))
0041               KAP1 = CSUBP/XLAMB*MOX70**2/(70.0D0**XN2*ZS70)
0042               KAP2 = KAP1                                                         469 0212
0043            20 TAV = (TAP + TF)/2.0D0                                              469 0213
0044               RETURN                                                              469 0216
0045           201 FORMAT (30H      AP CENTERED PRIMARY FLAME                         )469 0217
0046           202 FORMAT (30H      AP CENTERED FINAL FLAME                           )469 0218
0047           800 FORMAT (2I2)                                                        469 0219
0048           801 FORMAT (8A10)                                                       469 0220
0049           802 FORMAT (6E12.6)                                                     469 0221
0050               END                                                                 469 0222
```

```
              C      BEGINNING OF COMPETING FLAME CALCULATION                      469 0105
0045            51   I7 = 0                                                         469 0106
0046                 I8 = 0                                                         469 0107
0047                 ARGLST(1) = TS                                                 469 0108
0048                 ARGLST(3) = C3                                                 469 0109
0049                 ARGLST(4) = C4                                                 469 0110
0050                 ARGLST(5) = RATC                                               469 0111
0051                 ARGLST(6) = XNC                                                469 0112
              C      CONVERGENCE CALCULATION ON TS FOLLOWS                          469 0113
0052            80   XTS = TS - BOB(DON, ARGLST)                                    469 0114
0053                 IF (DABS (1.0D0- XTS/TS) - .001D0) 60, 60, 61
0054            61   IF (TS - XTS) 86, 85, 85
0055            85   I7 = 1                                                         469 0117
0056                 IF (XTS.LT.500.0D0) XTS = 500.0D0
0057                 XLOW = XTS
0058                 GO TO 87                                                       469 0119
0059            86   I8 = 1                                                         469 0120
0060                 IF(XTS.GE.1400.) XUP = 1400.0D0
0061                 IF(XTS.LT.1400.) XUP = XTS
0062            87   IF (I7 + I8 - 2) 88, 89, 89                                    469 0122
0063            88   ARGLST(1) = XTS                                                469 0123
0064                 GO TO 80                                                       469 0124
0065            89   ANS = 0.0D0                                                    469 0125
              C      TS HAS BOUNCED  --  GO TO BRUTE FORCE                          469 0126
0066                 N = 15                                                         469 0127
0067                 XTS = [illegible]2(DON, ARGLST, XUP, XLOW, ANS, N)             469 0128
0068            60   CONTINUE                                                       469 0129
0069            62   R = MT/RHOP                                                    469 0130
0070                 RETURN                                                         469 0131
0071                 END                                                            469 0132

              C      ********                    FINRAT                    ********
0001                 SUBROUTINE FINRAT (XMT,D,FZERO,DDO,XXNU,NCOUNT)
0002                 IMPLICIT REAL*8 (A-H,O-Z)
0003                 COMMON/XRAT/ RHOP,BR
0004                 DIMENSION XMT(100), FZERO(100), XXNU(100), D(100)
0005                 A = 0.0D0
0006                 LL = 1
0007             2   XL1 = XMT(LL)*XXNU(LL)*FZERO(LL)/D(LL)
0008                 XL2 = XMT(LL+1)*XXNU(LL+1)*FZERO(LL+1)/D(LL+1)
0009                 IF(D(LL+1).LT.5.0D0) GO TO 10
0010                 IF(D(LL+1).LT.30.0D0) GO TO 11
0011                 IF(D(LL+1).LT.60.0D0) GO TO 12
0012                 IF(D(LL+1).LT.120.0D0) GO TO 13
0013                 IF(D(LL+1).LT.240.0D0) GO TO 14
0014                 GO TO 15
0015            10   DDO = .5D0
0016                 GO TO 3
0017            11   DDO = 1.0D0
0018                 GO TO 3
0019            12   DDO = 5.0D0
0020                 GO TO 3
0021            13   DDO = 10.0D0
0022                 GO TO 3
0023            14   DDO = 20.0D0
0024                 GO TO 3
0025            15   DDO = 40.0D0
0026             3   APART = (XL1 + XL2)*DDO/2.0D0
0027                 LL = LL + 1
0028                 A = A + APART
0029                 IF (LL - NCOUNT) 2, 4, 4
0030             4   BR = A/RHOP
0031                 RETURN
0032                 END
```

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               C      ******                    DON                         ******
 0001                 DOUBLE PRECISION FUNCTION DON (ARGLST)
 0002                 IMPLICIT REAL*8 (A-H,O-Z)
               C      CALCULATE TS FOR COMPETING FLAMES                                    469 0224
 0003                 REAL*8 KAP1, KAP2, KPF, MOX, MT
 0004                 COMMON A1,        A2,       AF,       AFH,      ALFAST,   ANSI(50),469 0004
                     1      AOX,        BESS,     BESSI(50),BETAF,    BSQR,                469 0227
                     2                  CIGN,     CON1,     CSUBP,    DELDI,    DZERO,     469 0228
                     3      EF,         EOX,      ETA,      GAMMA,    GMW,      HDN,       469 0229
                     4      HDP,                                      KAP1,     KAP2,
                     5      KPF,                  MOX,      MT,                 P,
                     6      POWO,       PCWIGN,   PSTART,   PSTOP,    QAP,      QFF        469 0232
 0005                 COMMON QFUEL,     QL,       QPF,      R,        RAP,      RF,        469 0233
                     1      RHOF,       RHOSP,    RHOX,     RON,      SOX,      TAP,       469 0012
                     2      TAV,        TF,       TIT(20),  TIT1(20), TZERO,               469 0235
                     3      XLAMM,      XN1,      XN2,      XN3,      XNUST,    XNU1       469 0014
 0006                 COMMON XNUP, XALFA, PMW, ETAP, EPS
 0007                 COMMON /PBC/ CONF                                                    469 0239
 0008                 COMMON /RWN/ BETA, RHOM, QM                                          469 0240
 0009                 COMMON/DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
 0010                 COMMON/XINT/ IJIM, IPLOT, K, MEM1, NP1
 0011                 DIMENSION ARGLST(20)                                                 469 0241
 0012                 IF (ARGLST(1).GT.0.230D40) GO TO 99
 0013                 TS = ARGLST(1)                                                       469 0242
 0014                 C3 = ARGLST(3)                                                       469 0243
 0015                 C4 = ARGLST(4)                                                       469 0244
 0016                 RATC = ARGLST(5)                                                     469 0245
 0017                 XNC = ARGLST(6)                                                      469 0246
 0018                 RHOP = RHOSP
 0019                 ALFA = ALFAST
 0020                 XNU = XNUST
 0021             80  C2P = GAMMA*TS**0.75D0/82.06D0*PMW
 0022                 C3P = 2.0D0*C2P*ETAP*AFH
 0023                 C4P = (7.66D0*C2P)**2/BSQR
 0024                 MOX = AOX*DEXP(-EOX/(1.987D0*TS))
 0025                 CALL SOXCAL (TS, SOX)                                                469 0251
 0026                 PT = MOX*SOX/ALFA                                                    469 0252
 0027                 XSTPF = MT/(KPF*P**XN1)                                              469 0253
 0028                 DUM2=1.0D0 + C4P/(MOX**2)
 0029                 IF (DUM2 - 1.01D0) 121, 121, 122
 0030            121  DUM3 = 0.5D0*C4P/(MOX**2)
 0031                 GO TO 124                                                            469 0257
 0032            122  DUM3 = DSQRT (DUM2) - 1.0D0
 0033            124  XSTPD = C3P/(MOX*DUM3)                                               469 0259
 0034                 IF(XSTPD.LT.0.0D0) XSTPD = 1.0D0
 0035                 XSTAP = MOX/(RATC*P**XNC)                                            469 0260
 0036                 IF (XSTAP - XSTPF - XSTPD/AFH) 51, 51, 52                            469 0261
 0037             52  BETAF = 1.0D0                                                        469 0262
 0038                 GO TO 55                                                             469 0263
 0039             51  BETAF = AFH*(XSTAP - XSTPF)/XSTPD                                    469 0264
 0040                 IF (CONF) 54, 54, 53                                                 469 0265
 0041             53  BETAF = 2.0D0*BETAF - BETAF**2
               C      CONICAL (CONICAL) FLAME                                              469 0267
 0042             54  IJIM = 2                                                             469 0268
 0043                 IF (BETAF) 56, 55, 55                                                469 0269
 0044             56  BETAF = 0.0D0                                                        469 0270
 0045             55  CONTINUE                                                             469 0271
 0046                 DUM2 = 1.0D0 + C4/(MOX**2)
```

```
0047            IF (DUM2 - 1.01D0) 10, 10, 11
0048       11   DUM3 = DSQRT (DUM2) - 1.0D0
0049            GO TO 91                                                      469 0275
0050       10   DUM3 = 0.5D0*C4/(MOX**2)
0051       91   XSTARD = C3/(MOX*DUM3)                                        469 0277
0052            IF(XSTARD.LT.0.0D0) XSTARD = 1.0D0
0053            DUM2 = 1.0D0 + C4P/(MOX**2)
0054            IF (DUM2 - 1.01D0) 12, 12, 13
0055       13   DUM3 = DSQRT(DUM2) - 1.0D0
0056            GO TO 92                                                      469 0281
0057       12   DUM3 = 0.5D0*C4P/(MOX**2)
0058       92   XSTPD = C3P/(MOX*DUM3)                                        469 0283
0059            IF(XSTPD.LT.0.0D0) XSTPD = 1.0D0
0060       93   XSTAP = MOX/(RATC*P**XNC)                                     469 0284
0061       94   XSTPF = MT/(KPF*P**XN1)                                       469 0285
0062       95   ZAP = CSUBP*MOX*XSTAP/XLAMB                                   469 0286
0063       96   ZAT = ZAP + CSUBP*MCX*XSTARD/XLAMB                            469 0287
0064            IF (BETAF - 1.0D0) 97, 90, 90
0065       90   ZPF = CSUBP*MT/XLAMB*(XSTPF + XSTPD)                          469 0289
0066            GO TO 98                                                      469 0290
0067       97   ZPF = CSUBP*MT/XLAMB*(XSTAP*AFH + XSTPF)                      469 0291
0068       98   IF (ZPF.LT.-164.0D0) ZPF = -164.0D0
0069            IF (ZAP.LT.-164.0D0) ZAP = -164.0D0
0070            IF (ZAT.LT.-164.0D0) ZAT = -164.0D0
0071            IF (ZPF.GT.164.0D0) ZPF = 164.0D0
0072            IF (ZAP.GT.164.0D0) ZAP = 164.0D0
0073            IF (ZAT.GT.164.0D0) ZAT = 164.0D0
0074            XTS = TZERO - ALFA*QL/CSUBP - (1.0D0 - ALFA - BETA)*QFUEL/CSUBP
               1 - BETA*QM/CSUBP + (1.0D0 - BETAF)*(ALFA*QAP/CSUBP*DEXP(-ZAP) +
               2 QFF/CSUBP*DEXP(-ZAT)*ALFA)+ BETAF*QPF/CSUBP*DEXP(-ZPF)
          C     XTS = AMAX1 (XTS, 500.)                                       469 0295
0075            IF ( XTS.LE.500.0D0) XTS = 500.0D0
0076            DON = ARGLST(1) - XTS                                         469 0296
0077            GO TO 100
0078       99   DON = ARGLST(1)
0079      100   RETURN                                                        469 0297
0080            END                                                           469 0298
```

```
                C      ******                      OUTPUT                        ******
0001                   SUBROUTINE OUTPUT (M1)                                          469 0327
0002                   IMPLICIT REAL*8 (A-H,C-Z)
0003                   REAL*8 KAP1, KAP2, KPF, MOX, MT
0004                   REAL*8 MOX1
0005                   COMMON A1,        A2,       AF,        AFH,      ALFAST,   ANSI(50),469 0004
                     1        AOX,       BESS,     BESSI(50),BETAF,    BSQR,               469 0330
                     2                   CIGN,     CCN1,      CSURP,    CELDI,    DZERO,   469 0331
                     3        FF,        EOX,      ETA,       GAMMA,    GMW,      HDN,     469 0332
                     4        HOP,                                      KAP1,     KAP2,
                     5        KPF,                 MOX,       MT,                 P,
                     6        POWD,      POWIGN,   PSTART,    FSTOP,    OAP,      OFF      469 0335
0006                   COMMON QFUEL,     QL,       CPF,       R,        RAP,      RF,      469 0336
                     1        RHOF,      RHOSP,    RHOX,      PON,      SOX,      TAP,     469 0012
                     2        TAV,       TF,       DPH(20),   TIT1(20), TZERO,             469 0338
                     3        XLAMB,     XN1,      XN2,       XN3,      XNUST,    XNU1     469 0014
0007                   COMMON XNUP, XALFA, PMW, ETAP, EPS
0008                   COMMON /PBC/ CONF                                               469 0342
0009                   COMMON /RWN/ BETA, RHOP, QM                                     469 0343
0010                   COMMON/DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
0011                   COMMON/XINT/ IJIM, IPLOT, K, MEM1, NP1
0012                   DIMENSION TIT(20)                                               469 0344
0013                   DIMENSION BR(30), PT(30), BRA(30), PTA(30)
0014                   GO TO (10, 20), M1                                              469 0352
0015             10    BR(K) = R                                                       469 0353
0016                   PT(K) = P                                                       469 0354
0017                   PTA(K) = PT(K)*14.700
0018                   BRA(K) = BR(K)/2.5400
0019                   KMAX = K                                                        469 0367
0020                   K = K + 1                                                       469 0368
0021                   RETURN                                                          469 0371
0022             20    CONTINUE
0023                   XNUT = XALFA*100.000
0024                   TZIP = TZERO - 273.000                                          469 0376
0025                   IF (CONF) 150, 150, 151                                         469 0377
0026            151    WRITE (6,152)                                                   469 0378
0027            150    WRITE (6,154)                                                   469 0380
0028            153    WRITE (6,106)                                                   469 0381
0029                   WRITE (6,107) XNUT
0030                   WRITE (6,105) RHOP, RHOF, RHOX                                  469 0383
0031                   WRITE (6,109) QFUEL, TF, GMW, PMW                               469 0384
0032                   WRITE (6,110) GAMMA, XNU1,XNUP
0033                   WRITE (6,111)                                                   469 0386
0034                   WRITE (6,112) CIGN, POWIGN, POWD, QL                            469 0387
0035                   WRITE (6,113)                                                   469 0388
0036                   WRITE (6,114) EF, EOX, AF, AOX                                  469 0389
0037                   WRITE (6,115) XN1, KPF, XN2, KAP1, XN3, KAP2                    469 0390
0038                   WRITE (6,116)                                                   469 0391
0039                   WRITE (6,117) TAP, XLAMB, CSURP                                 469 0392
0040                   WRITE (6,118) AFH
0041                   WRITE (6,119) TZIP                                              469 0394
0042                   WRITE (6,121) EPS                                               469 0395
0043                   WRITE(6,102)
0044                   WRITE(6,104)
0045                   DO 69 K = 1, KMAX
0046                   WRITE(6,103) PT(K),PTA(K),BR(K),BRA(K)
0047             69    CONTINUE
0048                   RETURN
```

```
0049      101  FORMAT (1H1,8A10/)                                                 469 0440
0050      102  FORMAT(8X,4HPRES,5X,4HPRES,7X,2HBR,9X,2HBR)
0051      103  FORMAT (5X,F7.2,2X,F7.1,2(2X,F9.4))
0052      104  FORMAT(8X,4HATMS,5X,4HPSIA,5X,6HCM/SEC,5X,6HIN/SEC/)
0053      106  FORMAT (19H PROPELLANT DATA IS)                                    469 0448
0054      107  FORMAT (6X,20HWT. PERCENT OXID. = ,F6.1)
0055      108  FORMAT (6X,16HPROP. DENSITY = ,F5.2,9X,17HBINDER DENSITY = ,F5.2, 469 0453
              1 9X,16HOXID. DENSITY = ,F5.2)                                     469 0454
0056      109  FORMAT (6X,8HQFUEL = ,F6.1,5X,12HTF(DEG K) = ,F6.0,5X,9HMOL WT = ,469 0455
              1 F6.2,5X,13HPRI MOL WT = ,F6.2)                                   469 0456
0057      110  FORMAT (6X,13HDIFF PARAM = ,F11.4,3X,9HST RAT = ,F6.2,3X,13HPRI ST
              1 RAT = ,F6.2/)
0058      111  FORMAT (38H OXIDIZER IGNITION AND BURNING DATA IS)                 469 0459
0059      112  FORMAT (6X,7HCIGN = ,F6.1,6X,9HPOWIGN = ,F6.3,6X,7HPOWD = ,F6.1,  469 0460
              1 6X, 14HLATENT HEAT = ,F7.1/)                                     469 0461
0060      113  FORMAT (41H ACTIVATION ENERGIES AND RATE FACTORS ARE)              469 0462
0061      114  FORMAT (6X,5HEF = ,F8.0,6X,7HE OX = ,F8.0,6X,5HAF = ,E10.3,6X,    469 0463
              1 7HA OX = , E10.3)                                                469 0464
0062      115  FORMAT (6X,11HORDER, PF =,F6.3,3X,12HRT CON, PF =,E10.3,3X,       469 0465
              1 11HORDER, LP =,F6.3,3X,12HRT CON, LP =,E10.3/                    469 0466
              2 6X,11HORDER, HP =,F6.3,3X,12HRT CON, HP =,E10.3/)                469 0467
0063      116  FORMAT (21H FLAME PROPERTIES ARE)                                  469 0468
0064      117  FORMAT (6X,17HOXID. FLM TEMP = ,F7.1,9X,14HGAS CONDUCT = ,F8.5,   469 0469
              1 9X,10HCP(AVE) = ,F7.4)                                           469 0470
0065      118  FORMAT(6X,17HAV FLM HT FACT = ,F7.4/)
0066      119  FORMAT (27H PROPELLANT INITIAL TEMP IS,F6.1,15H DEG CENTIGRADE//) 469 0473
0067      120  FORMAT(//5X,12HCASE NUMBER ,F3.0)                                  469 0474
0068      121  FORMAT (47H EXPONENT FOR DIFFUSION PRESSURE DEPENDENCE IS ,F6.3/) 469 0475
0069      152  FORMAT (30H      CONICAL FLAME ASSUMED                   /)       469 0476
0070      154  FORMAT (1H1,30H      PARABOLIC FLAME ASSUMED               /)
0071           END                                                                469 0478

          C    ******                     SOXCAL                         ******
0001           SUBROUTINE SOXCAL (TS1, SOX1)                                      469 0299
0002           IMPLICIT REAL*8 (A-H,O-Z)
0003           REAL*8 KAP1, KAP2, KPF, MOX, MT
0004           COMMON A1,      A2,      AF,      AFH,      ALFAST,   ANSI(50),469 0004
              1       AOX,     BESS,    BESSI(50),BETAF,   BSQR,               469 0302
              2                CIGN,    CON1,    CSUBP,    DELDI,    DZERO,    469 0303
              3       EF,      EOX,     ETA,     GAMMA,    GMW,      HDN,      469 0304
              4       HDP,                                  KAP1,     KAP2,
              5       KPF,              MOX,     MT,                 P,
              6       POWD,    POWIGN,  PSTART,  PSTOP,    QAP,      QFF       469 0307
0005           COMMON QFUEL,   QL,      QPF,     R,        RAP,      RF,       469 0308
              1       RHOF,    RHOSP,   RHOX,    RON,      SOX,      TAP,      469 0012
              2       TAV,     TF,      TIT(20), TIT1(20), TZERO,              469 0310
              3       XLAMB,   XN1,     XN2,     XN3,      XNUST,    XNU1      469 0014
0006           COMMON XNUP, XALFA, PMW, ETAP, EPS
0007           COMMON/DOUBLE/TS,C3P,C4P,XSTPF,XSTPD,XSTARD,XSTAP
0008           COMMON/XINT/ IJIM, IPLOT, K, MEM1, NP1
0009           RHOP = RHOSP
0010           ALFA = ALFAST
0011           XNU = XNUST
0012           RF = AF*DEXP(-EF/(1.987D0*TS1))/RHOF
0013           RAP = MOX/RHOX                                                     469 0315
0014           RON = RAP*CIGN*(DZERO*.0001D0)**POWD/(P**POWIGN)
0015           HDP = A1*(1.0D0 - RAP/RF) + RON
0016           HDN = A2*(1.0D0 - RAP/RF) + RON
0017           IF (HDP.GE.0.7885D0)  HDP = 0.7885D0
0018           IF (HDP.LE.-0.2115D0) HDP = -0.2115D0
0019           IF (HDN.GE.0.2115D0) HDN = 0.2115D0
0020           IF (HDN.LE.-0.7885D0) HDN = 0.7885D0
0021           SOX1 = 3.0D0*XNU*(HDP**2 + HDN**2 + 1.0D0/3.0D0)/(1.0D0 + 3.0D0*
              1 XNU*(HDP**2 + HDN**2))
0022           RETURN                                                             469 0325
0023           END                                                                469 0326
```

```
            C      ******                     CONVR2                        ******
0001               DOUBLE PRECISION FUNCTION CONVR2 (XNAME,ARGLST,XUP,XLOW,ANS,N)
0002               IMPLICIT REAL*8 (A-H,O-Z)
            C                                                                     469 0480
            C      THIS CONVERGENCE ROUTINE IS FOR USE WHEN UPPER AND LOWER       469 0481
            C       EXTREMES ARE KNOWN                                            469 0482
            C                                                                     469 0483
            C       ARGUMENTS ARE -                                               469 0484
            C           XNAME........NAME OF USER FUNCTION TO EVALUATE CONVERGENCE  469 0485
            C                        EXPRESSION. (SPECIFIED AS EXTERNAL IN CALLING  469 0486
            C                        PROGRAM)                                     469 0487
            C           ARGLST( )....ARRAY CONTAING THE ARGUMENTS REQUIRED BY XNAME.  469 0488
            C                        (ARG(1) WILL BE THE CURRENT ITERATION GUESS)  469 0489
            C           XUP,XLOW.....UPPER AND LOWER INDEPENDENT VARIABLE VALUES  469 0490
            C           ANS..........VALUE TO WHICH EXPRESSION SHOULD CONVERG     469 0491
            C           N............NUMBER OF INTERVAL HALVING STEPS DESIRED     469 0492
            C                                                                     469 0493
0003               DIMENSION ARGLST(2)                                            469 0494
            C                                                                     469 0495
            C      SET INITIAL GUESS AT BOTTOM HALF AND EVALUATE                  469 0496
            C                                                                     469 0497
0004               BOT=XLOW                                                       469 0498
0005               XINC=(XUP-XLOW)*0.5D0                                          469 0499
0006               TOP=XLOW+XINC                                                  469 0500
0007               IVAL=N                                                         469 0501
0008               ARGLST(1)=BOT                                                  469 0502
0009               ABOT=XNAME(ARGLST)                                             469 0503
0010               ARGLST(1)=XUP                                                  469 0504
0011               ATOP=XNAME(ARGLST)                                             469 0505
0012               ABTOP = DABS(ATOP)
0013               ABBOT = DABS(ABOT)
0014               BTOP = ATOP/ABTOP
0015               BBOT = ABOT/ABBOT
0016               BTANS = ANS/ABTOP
0017               BBANS = ANS/ABBOT
0018               IF ((BTOP - BTANS)*(BBOT - BBANS)) 30, 30, 31
            C   31 IF (ABS(ATOP-ANS)-ABS(ABOT-ANS)) 32,32,33                      469 0507
0019            31 IF (DABS(ATOP-ANS)-DABS(ABOT-ANS)) 32,32,33
0020            32 CONVR2=XUP                                                     469 0508
0021               GO TO 99                                                       469 0509
0022            33 CONVR2=XLOW                                                    469 0510
0023               GO TO 99                                                       469 0511
0024            30 ARGLST(1)=TOP                                                  469 0512
0025               ATOP=XNAME(ARGLST)                                             469 0513
            C                                                                     469 0514
            C      CHECK IF SOLUTION IS IN THE INTERVAL                           469 0515
            C                                                                     469 0516
0026            50 CONTINUE                                                       469 0517
0027               ABTOP = DABS(ATOP)
0028               ABBOT = DABS(ABOT)
0029               BTOP = ATOP/ABTOP
0030               BBOT = ABOT/ABBOT
0031               BTANS = ANS/ABTOP
0032               BBANS = ANS/ABBOT
0033               IF ((BTOP - BTANS)*(BBOT - BBANS)) 1, 40, 2
            C                                                                     469 0519
            C      WITHIN THIS INTERVAL , HALVE IT                                469 0520
            C                                                                     469 0521
```

```
0034          1 XINC=XINC*0.500                                469 0522
0035            TOP=BOT+XINC                                   469 0523
0036            IVAL=IVAL-1                                    469 0524
0037            IF (IVAL) 12,12,11                             469 0525
0038         12 CONVR2=TOP                                     469 0526
0039            GO TO 99                                       469 0527
0040         11 ARGLST(1)=TOP                                  469 0528
0041            ATOP=XNAME(ARGLST)                             469 0529
0042            GO TO 50                                       469 0530
          C                                                    469 0531
          C     IN THE NEXT INTERVAL , MOVE AND HALVE          469 0532
          C                                                    469 0533
0043          2 XINC=XINC*0.500                                469 0534
0044            BOT=TOP                                        469 0535
0045            TOP=BOT+XINC                                   469 0536
0046            ABOT=ATOP                                      469 0537
0047            IVAL=IVAL-1                                    469 0538
0048            IF (IVAL) 22,22,21                             469 0539
0049         22 CONVR2=TOP                                     469 0540
0050            GO TO 99                                       469 0541
0051         21 ARGLST(1)=TOP                                  469 0542
0052            ATOP=XNAME(ARGLST)                             469 0543
0053            GO TO 50                                       469 0544
          C                                                    469 0546
          C     ONE OF THE END POINTS IS EXACT                 469 0547
          C                                                    469 0548
0054         40 IF (ATOP-ANS) 42,41,42                         469 0549
0055         41 CONVR2=TOP                                     469 0550
0056            GO TO 99                                       469 0551
0057         42 CONVR2=BOT                                     469 0552
0058         99 CONTINUE                                       469 0553
0059            ARGLST(1) = CONVR2                             469 0554
0060            ADUM = XNAME (ARGLST)                          469 0555
0061            RETURN                                         469 0556
0062            END                                            469 0557
```

```
                                       BESSEL                         ******
         C      ******                                                          469 0558
0001            SUBROUTINE BESSEL(X,Y,ANS)
0002            IMPLICIT REAL*8 (A-H,O-Z)                                       469 0559
0003            DIMENSION ANS(4)                                                469 0560
         C                                                                      469 0561
         C      CN RETURN                                                       469 0562
         C       ANS(1)= J ZERO (X)                                             469 0563
         C       ANS(2)= Y ZERO (X)                                             469 0564
         C       ANS(3)= J ONE  (Y)                                             469 0565
         C       ANS(4)= Y ONE  (Y)                                             469 0566
         C
0004            IF(X-3.0D0) 2,2,4                                               469 0568
0005          2 Z=X*X/9.0D0                                                     469 0569
0006            IF(X)20,20,30                                                   469 0570
0007         20 ANS(1)=1.0D0                                                    469 0571
0008            ANS(2)=1.0D0                                                    469 0572
0009            GO TO 6                                                         469 0573
0010         30 CONTINUE
0011            ANS(1) = (((((.0002100*Z-.0039444D0)*Z+.0444479D0)*Z-.3163866D0)*Z
               1 + 1.2656208D0)*Z-2.2499997D0)*Z+1.0D0
0012            ANS(2) = .63662031* DLOG(.5D0*X)*ANS(1)+(((((-.0002484600*Z+
               1 .00427916D0)*Z-.04261214D0)*Z+.25300117D0)*Z-.74350384D0)*Z+
               2 .60559366D0)*Z+.36746691                                       469 0578
0013            GO TO 6
0014          4 Z=3.0D0/X
0015            FZERO = (((((.0001447600*Z-.00072805D0)*Z+.00137237D0)*Z-.00009512
               1D0)*Z-.0055274D0)*Z-.7700D-6)*Z+.7978845600
0016            THZERO = X+(((((.00013558D0*Z-.00029333D0)*Z-.00054125D0)*Z+.00262
               1573D0)*Z-.00003954D0)*Z-.04166397D0)*Z-.78539816D0
0017            ANS(1) = FZERO*DCOS(THZERO)/DSQRT(X)                            469 0586
0018            ANS(2) = FZERO*DSIN(THZERO)/DSQRT(X)                            469 0587
0019          6 IF(Y-3.)8,8,10                                                  469 0588
0020          8 Z=Y*Y/9.0D0                                                     469 0589
0021            IF(Y)40,40,50                                                   469 0590
0022         40 ANS(3)=0.0D0                                                    469 0591
0023            ANS(4)=0.0D0                                                    469 0592
0024            GO TO 80
0025         50 CONTINUE
0026            ANS(3) = ((((((.00001109D0*Z-.00031761D0)*Z+.00443319D0)*Z-
               1 .03954289D0)*Z+.21093573D0)*Z-.56249985D0)*Z+.5D0)*Y
0027            ANS(4) = (.63662031D0*Y* DLOG(.5D0*Y)*ANS(3)+(((((.0027873D0*Z-
               1 .0400976D0)*Z+.3123951D0)*Z-1.3164827D0)*Z+2.1682709D0)*Z+.221209
               21D0)*Z-.6366198D0)/Y                                            469 0597
0028         80 RETURN
0029         10 Z=3.0D0/Y
0030            FONE = (((((-.00020033D0*Z+.00113653D0)*Z-.00249511D0)*Z+.00017105
               1D0)*Z+.01659667D0)*Z+1.5600D-6)*Z+.7978845600
0031            THONE = Y+(((((-.00029166D0*Z+.00079824D0)*Z+.00074348D0)*Z-
               1 .00637879D0)*Z+.00005650D0)*Z+.12499612D0)*Z-2.35619450D0
0032            ANS(3) = FONE*DCOS(THONE)/DSQRT(Y)                              469 0605
0033            ANS(4) = FONE*DSIN(THONE)/DSQRT(Y)                              469 0606
0034            RETURN
0035            END
                                          BOB                         ******
         C      ******
0001            DOUBLE PRECISION FUNCTION BOB (XNAME,ARGLST)
0002            IMPLICIT REAL*8 (A-H,O-Z)                                       469 0608
0003            DIMENSION ARGLST(20)                                            469 0609
0004            BOB = XNAME(ARGLST)                                             469 0610
0005            RETURN
0006            END
```

```
              C      ********                 INPUT1                        ********
0001                 SUBROUTINE INPUT1(JJ,M,D,FZERO,XNU,NCOUNT,DDO)
0002                 IMPLICIT REAL*8 (A-H,O-Z)
0003                 REAL*8 KAP1,KAP2,KPF,MOX,MT
0004                 COMMON A1,       A2,       AF,       AFH,      ALFAST,   ANSI(50),
                    1       ADX,      BESS,     BESSI(50),BETAF,    BSCR,
                    2                 CIGN,     CON1,     CSUBP,    DELDI,    DZERO,
                    3       FF,       ECX,      ETA,      GAMMA,    GMW,      HON,
                    4       HOP,                                    KAP1,     KAP2,
                    5       KPF,                MOX,      MT,                 P,
                    6       POWD,     POWIGN,   PSTART,   PSTOP,    QAP,      QFF
0005                 COMMON QFUEL,    QL,       QPF,      R,        RAP,      RF,
                    1       RHOF,     RHOSP,    RHOX,     RON,      SOX,      TAP,
                    2       TAV,      TF,       TIT(20),  TIT1(20), TZERO,
                    3       XLAMB,    XN1,      XN2,      XN3,      XNUST,    XNU1
0006                 COMMON XNUP, XALFA, PMW, ETAP, EPS
0007                 COMMON/XPUT/NXCCUN
0008                 COMMON/XRAT/ RHOP,BR
0009                 DIMENSION YI(10), FZERO(100), D(100), XFZERO(1000), XD(1000), DBAR
                    1I(10), SIGMAI(10)
0010                 IF(M - 1) 1, 1, 15
0011             1   READ(5,100) NMODES, NCCUNT,NXCOUN,XN,DDO,XDDO
0012                 DI = 1.0D0
0013                 FSUM = 0.0D0
0014                 JJ = 1
0015                 DO 10 II=1,NMODES
0016                 READ(5,101) SIGMAI(II), DBARI(II), YI(II)
0017            10   CONTINUE
0018                 DO 12 III=1,NXCOUN
0019                 DO 11 JJJ=1,NMODES
0020                 CALL DISTF(DI, JJJ, III, YVECR, DBARI, SIGMAI)
0021                 XFSUM = YI(JJJ)/YVECR
0022                 FSUM = FSUM + XFSUM
0023            11   CONTINUE
0024                 XFZERO(III) = FSUM
0025                 XD(III) = DI
0026                 DI = DI + XDDO
0027                 FSUM = 0.0D0
0028            12   CONTINUE
0029            13   CONTINUE
0030                 XNU = 1.0D0/(1.0D0 + RHOX*(1.0D0-XALFA)/(RHOF*XALFA))
0031                 RHOP = RHOF*RHOX/(RHOF*XALFA+RHOX*(1.0D0-XALFA))
0032                 CALL CCAL (XFZERO,XD,XN,XNU,C,XDDO)
0033            14   CONTINUE
              C      RE-COUNT D AND FZERO
0034                 DI = .5D0
0035                 DO 22 IZZ=1,NCOUNT
0036                 FSUM = 0.0D0
0037                 DO 21 JZZ=1,NMODES
0038                 CALL DISTF(DI,JZZ,IZZ,YVECR,DBARI,SIGMAI)
0039                 XFSUM = YI(JZZ)/YVECR
0040                 FSUM = FSUM + XFSUM
0041            21   CONTINUE
0042                 FZERO(IZZ) = FSUM
0043                 C(IZZ) = DI
0044                 IF(DI.LT.5.0D0) GO TO 31
0045                 IF(DI.LT.30.0D0) GO TO 32
0046                 IF(DI.LT.60.0D0) GO TO 33
```

```
              IF(DI.LT.120.0D0) GO TO 34
              IF(DI.LT.240.0D0) GO TC 35
              GO TO 36
         31   CI = DI + .5D0
              GO TO 22
         32   DI = DI + 1.0D0
              GO TO 22
         33   CI = DI + 5.0D0
              GO TO 22
         34   CI = DI + 10.0D0
              GO TO 22
         35   CI = DI + 20.0D0
              GO TO 22
         36   DI = DI + 40.0D0
         22   CONTINUE
         15   CONTINUE
              DZERO = D(JJ)
              XNUST = 1.0D0/(1.0D0+(6.0D0*C*DZERO**(XN-3.0D0))/3.141592D0)
              ALFAST = 1.0D0/(1.0D0+(6.0D0*C*RHOF*DZERO**(XN-3.0D0))/(3.141592D0
             1 *RHOX))
              RHOSP = RHOX*XNUST/ALFAST
              RETURN
        100   FORMAT(3I5,3F10.5)
        101   FORMAT(3F10.5)
              END
C             ********                     CCAL                   ********
              SUBROUTINE CCAL(XFZERO,XD,XN,XNU,C,XD00)
              IMPLICIT REAL*8 (A-H,O-Z)
              COMMON/XPUT/NXCCUN
              DIMENSION XFZERO(1000), XD(1000)
              A = 0.0D0
              B1 = 3.141592D0*(1.0D0-XNU)/(6.0D0*XNU)
              JZ = 1
          2   XL1 = XFZERO(JZ)*XD(JZ)**(XN-4.0D0)
              XL2 = XFZERO(JZ+1)*XD(JZ+1)**(XN-4.0D0)
              APART = (XL1 + XL2)*XD00/2.0D0
              JZ = JZ + 1
              A = A + APART
              IF (JZ - NXCOUN) 2, 4, 4
          4   C = B1/A
              RETURN
              END
C             ********                     DISTF                  ********
              SUBROUTINE DISTF(DI,JJJ,III,YVECR,DBARI,SIGMAI)
              IMPLICIT REAL*8 (A-H,O-Z)
              DIMENSION DBARI(10), SIGMAI(10)
              X = DLOG(DI)
              XM = DLOG(DBARI(JJJ))
              SIG = DLOG(SIGMAI(JJJ))
              YVECR = SIG*2.5066282750D0*DEXP(.5D0*((X-XM)/SIG)**2)
              RETURN
              END
C             ********                     XSTOR                  ********
              SUBROUTINE XSTOR (JJ,XMT,XNUST,XNU,MT,XXNU)
              IMPLICIT REAL*8 (A-H,O-Z)
              REAL*8 MT
              DIMENSION XMT(100), XXNU(100)
              XMT(JJ) = MT
              XXNU(JJ) = XNU/XNUST
              JJ = JJ + 1
              RETURN
              END
```

p = 2 atm

JJ	R, Cm/sec	FZEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α*	XNUST, ξ*
1	0.0022	0.0000	0.5	0.33	2.14	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.41	2.76	10000.00	10000.00	0.2759	0.1601
3	0.2187	0.0008	1.5	36.86	280.44	5.04	6.31	0.3637	0.2223
4	0.2180	0.0032	2.0	38.37	296.27	3.05	3.57	0.4325	0.2759
5	0.2144	0.0080	2.5	39.11	305.36	2.57	2.99	0.4878	0.3227
6	0.2108	0.0156	3.0	39.65	312.34	2.37	2.77	0.5334	0.3637
7	0.2076	0.0260	3.5	40.08	318.06	2.27	2.69	0.5714	0.4001
8	0.2048	0.0389	4.0	40.46	322.98	2.21	2.66	0.6038	0.4325
9	0.2023	0.0539	4.5	40.78	327.25	2.16	2.65	0.6316	0.4616
10	0.2001	0.0704	5.0	41.06	331.18	2.12	2.66	0.6558	0.4879
11	0.1965	0.1057	6.0	41.56	337.86	2.05	2.68	0.6957	0.5334
12	0.1937	0.1413	7.0	41.98	343.44	1.94	2.70	0.7273	0.5715
13	0.1915	0.1745	8.0	42.35	348.31	1.80	2.69	0.7530	0.6039
14	0.1898	0.2039	9.0	42.71	352.78	1.60	2.65	0.7742	0.6317
15	0.1887	0.2287	10.0	43.10	357.20	1.27	2.58	0.7921	0.6558
16	0.1869	0.2487	11.0	43.22	359.35	1.42	2.47	0.8074	0.6770
17	0.1829	0.2640	12.0	42.76	356.47	2.81	2.31	0.8205	0.6957
18	0.1785	0.2751	13.0	42.15	352.25	4.51	2.09	0.8320	0.7124
19	0.1729	0.2825	14.0	41.17	344.87	7.07	1.77	0.8421	0.7274
20	0.1643	0.2865	15.0	39.45	331.10	11.50	1.02	0.8511	0.7408
21	0.1486	0.2878	16.0	35.91	302.13	21.07	2.65	0.8591	0.7530
22	0.1006	0.2867	17.0	24.48	206.61	56.90	4.09	0.8663	0.7641
23	0.0679	0.2837	18.0	16.61	140.52	10000.00	5.88	0.8727	0.7743
24	0.0673	0.2791	19.0	16.55	140.24	10000.00	8.35	0.8786	0.7836
25	0.0666	0.2732	20.0	16.46	139.67	10000.00	12.06	0.8840	0.7921
26	0.0657	0.2665	21.0	16.31	138.55	10000.00	18.29	0.8889	0.8001
27	0.0642	0.2590	22.0	16.01	136.18	10000.00	30.98	0.8934	0.8074
28	0.0608	0.2509	23.0	15.22	129.60	10000.00	70.68	0.8976	0.8142
29	0.0512	0.2425	24.0	12.86	109.65	10000.00	10000.00	0.9014	0.8206
30	0.0513	0.2339	25.0	12.91	110.18	10000.00	10000.00	0.9050	0.8265
31	0.0513	0.2252	26.0	12.96	110.67	10000.00	10000.00	0.9083	0.8321
32	0.0513	0.2164	27.0	13.00	111.12	10000.00	10000.00	0.9114	0.8373
33	0.0513	0.2077	28.0	13.04	111.54	10000.00	10000.00	0.9143	0.8422
34	0.0514	0.1992	29.0	13.08	111.93	10000.00	10000.00	0.9170	0.8468
35	0.0514	0.1907	30.0	13.11	112.30	10000.00	10000.00	0.9195	0.8511
36	0.0514	0.1521	35.0	13.25	113.85	10000.00	10000.00	0.9302	0.8696
37	0.0514	0.1201	40.0	13.36	115.02	10000.00	10000.00	0.9384	0.8840
38	0.0514	0.0946	45.0	13.45	115.95	10000.00	10000.00	0.9449	0.8956
39	0.0514	0.0746	50.0	13.51	116.69	10000.00	10000.00	0.9501	0.9050
40	0.0514	0.0593	55.0	13.56	117.31	10000.00	10000.00	0.9545	0.9129
41	0.0514	0.0477	60.0	13.61	117.83	10000.00	10000.00	0.9581	0.9196
42	0.0514	0.0344	70.0	13.67	118.64	10000.00	10000.00	0.9639	0.9303
43	0.0514	0.0340	80.0	13.73	119.26	10000.00	10000.00	0.9682	0.9384
44	0.0513	0.0484	90.0	13.77	119.75	10000.00	10000.00	0.9717	0.9449
45	0.0513	0.0798	100.0	13.80	120.14	10000.00	10000.00	0.9744	0.9501
46	0.0513	0.1283	110.0	13.82	120.46	10000.00	10000.00	0.9767	0.9545
47	0.0513	0.1915	120.0	13.85	120.72	10000.00	10000.00	0.9786	0.9581
48	0.0513	0.3402	140.0	13.88	121.15	10000.00	10000.00	0.9816	0.9639
49	0.0512	0.4770	160.0	13.91	121.46	10000.00	10000.00	0.9839	0.9682
50	0.0512	0.5651	180.0	13.93	121.71	10000.00	10000.00	0.9856	0.9717
51	0.0512	0.5932	200.0	13.94	121.91	10000.00	10000.00	0.9870	0.9744
52	0.0511	0.5697	220.0	13.94	121.91	10000.00	10000.00	0.9882	0.9767
53	0.0512	0.5120	240.0	13.97	122.21	10000.00	10000.00	0.9892	0.9786
54	0.0512	0.3596	280.0	13.98	122.43	10000.00	10000.00	0.9907	0.9816
55	0.0511	0.2235	320.0	13.93	122.43	10000.00	10000.00	0.9919	0.9839
56	0.0512	0.1289	360.0	14.01	122.71	10000.00	10000.00	0.9928	0.9856
57	0.0511	0.0710	400.0	14.00	122.71	10000.00	10000.00	0.9935	0.9871
58	0.0511	0.0381	440.0	14.00	122.71	10000.00	10000.00	0.9941	0.9882
59	0.0511	0.0201	480.0	14.03	122.97	10000.00	10000.00	0.9946	0.9892
60	0.0511	0.0105	520.0	14.03	122.97	10000.00	10000.00	0.9950	0.9900

p = 3.54 atm

JJ	R, cm/sec	FZEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α*	XNUST, ζ*
1	0.0022	0.0000	0.5	0.14	0.77	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.17	0.99	10000.00	10000.00	0.2759	0.1601
3	0.3166	0.0008	1.5	22.66	148.37	5.04	6.31	0.3637	0.2223
4	0.3198	0.0032	2.0	23.90	158.54	3.05	3.57	0.4325	0.2759
5	0.3155	0.0080	2.5	24.44	163.63	2.57	2.99	0.4876	0.3227
6	0.3106	0.0156	3.0	24.80	167.27	2.37	2.77	0.5334	0.3637
7	0.3060	0.0260	3.5	25.09	170.22	2.27	2.69	0.5714	0.4001
8	0.3019	0.0389	4.0	25.33	172.67	2.21	2.66	0.6038	0.4325
9	0.2983	0.0539	4.5	25.53	174.79	2.16	2.65	0.6316	0.4616
10	0.2951	0.0704	5.0	25.71	176.67	2.12	2.66	0.6558	0.4879
11	0.2899	0.1057	6.0	26.03	179.97	2.05	2.68	0.6957	0.5334
12	0.2858	0.1413	7.0	26.30	182.85	1.94	2.70	0.7273	0.5715
13	0.2828	0.1745	8.0	26.56	185.42	1.80	2.69	0.7530	0.6039
14	0.2806	0.2039	9.0	26.81	187.86	1.60	2.65	0.7742	0.6317
15	0.2795	0.2287	10.0	27.10	190.45	1.27	2.58	0.7921	0.6558
16	0.2765	0.2487	11.0	27.15	191.31	1.42	2.47	0.8074	0.6770
17	0.2682	0.2640	12.0	26.63	188.07	2.81	2.31	0.8205	0.6957
18	0.2591	0.2751	13.0	25.98	183.88	4.51	2.09	0.8320	0.7124
19	0.2472	0.2825	14.0	25.00	177.78	7.07	1.77	0.8421	0.7274
20	0.2292	0.2865	15.0	23.36	165.94	11.50	1.02	0.8511	0.7408
21	0.1970	0.2878	16.0	20.22	143.97	21.07	2.65	0.8591	0.7530
22	0.1324	0.2867	17.0	13.68	97.58	56.90	4.09	0.8663	0.7641
23	0.1087	0.2837	18.0	11.30	80.73	10000.00	5.88	0.8727	0.7743
24	0.1075	0.2791	19.0	11.23	80.33	10000.00	8.35	0.8786	0.7836
25	0.1060	0.2732	20.0	11.12	79.67	10000.00	12.06	0.8840	0.7921
26	0.1039	0.2665	21.0	10.95	78.53	10000.00	18.29	0.8889	0.8001
27	0.1004	0.2590	22.0	10.63	76.33	10000.00	30.98	0.8934	0.8074
28	0.0930	0.2509	23.0	9.88	71.02	10000.00	70.68	0.8976	0.8142
29	0.0807	0.2425	24.0	8.60	61.91	10000.00	10000.00	0.9014	0.8206
30	0.0808	0.2339	25.0	8.64	62.22	10000.00	10000.00	0.9050	0.8265
31	0.0808	0.2252	26.0	8.67	62.50	10000.00	10000.00	0.9083	0.8321
32	0.0809	0.2164	27.0	8.70	62.77	10000.00	10000.00	0.9114	0.8373
33	0.0809	0.2077	28.0	8.73	63.01	10000.00	10000.00	0.9143	0.8422
34	0.0810	0.1992	29.0	8.76	63.25	10000.00	10000.00	0.9170	0.8468
35	0.0810	0.1907	30.0	8.78	63.46	10000.00	10000.00	0.9195	0.8511
36	0.0812	0.1521	35.0	8.88	64.37	10000.00	10000.00	0.9302	0.8696
37	0.0812	0.1201	40.0	8.96	65.06	10000.00	10000.00	0.9384	0.8840
38	0.0813	0.0946	45.0	9.02	65.60	10000.00	10000.00	0.9449	0.8956
39	0.0813	0.0746	50.0	9.07	66.04	10000.00	10000.00	0.9501	0.9050
40	0.0813	0.0593	55.0	9.11	66.40	10000.00	10000.00	0.9545	0.9129
41	0.0813	0.0477	60.0	9.14	66.70	10000.00	10000.00	0.9581	0.9196
42	0.0813	0.0344	70.0	9.19	67.17	10000.00	10000.00	0.9639	0.9303
43	0.0813	0.0340	80.0	9.22	67.53	10000.00	10000.00	0.9682	0.9384
44	0.0812	0.0484	90.0	9.25	67.82	10000.00	10000.00	0.9717	0.9449
45	0.0812	0.0798	100.0	9.27	68.04	10000.00	10000.00	0.9744	0.9501
46	0.0812	0.1283	110.0	9.29	68.23	10000.00	10000.00	0.9767	0.9545
47	0.0812	0.1915	120.0	9.31	68.38	10000.00	10000.00	0.9786	0.9581
48	0.0812	0.3402	140.0	9.33	68.63	10000.00	10000.00	0.9816	0.9639
49	0.0811	0.4770	160.0	9.35	68.81	10000.00	10000.00	0.9839	0.9682
50	0.0811	0.5651	180.0	9.36	68.96	10000.00	10000.00	0.9856	0.9717
51	0.0811	0.5932	200.0	9.38	69.07	10000.00	10000.00	0.9870	0.9744
52	0.0810	0.5697	220.0	9.37	69.07	10000.00	10000.00	0.9882	0.9767
53	0.0811	0.5120	240.0	9.39	69.25	10000.00	10000.00	0.9892	0.9786
54	0.0810	0.3596	280.0	9.40	69.37	10000.00	10000.00	0.9907	0.9816
55	0.0909	0.2235	320.0	9.40	69.37	10000.00	10000.00	0.9919	0.9839
56	0.0810	0.1289	360.0	9.42	69.54	10000.00	10000.00	0.9928	0.9856
57	0.0809	0.0710	400.0	9.42	69.54	10000.00	10000.00	0.9935	0.9871
58	0.0810	0.0381	440.0	9.43	69.64	10000.00	10000.00	0.9941	0.9882
59	0.0810	0.0201	480.0	9.43	69.64	10000.00	10000.00	0.9946	0.9892
60	0.0809	0.0105	520.0	9.43	69.64	10000.00	10000.00	0.9950	0.9900

p = 6.34 atm

JJ	R, cm/sec	FZEROP	DZERO, μ	XSTPF, μ	XS[illegible], μ	XSTPD, μ	XSTARD, μ	ALFAST, α*	XNUST, ζ*
1	0.0022	0.0000	0.5	0.06	0.27	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.07	0.35	10000.00	10000.00	0.2759	0.1601
3	0.4520	0.0008	1.5	13.50	76.09	5.04	6.31	0.3637	0.2223
4	0.4665	0.0032	2.0	14.54	82.95	3.05	3.57	0.4325	0.2759
5	0.4626	0.0080	2.5	14.95	85.87	2.57	2.99	0.4878	0.3227
6	0.4563	0.0156	3.0	15.20	87.79	2.37	2.77	0.5334	0.3637
7	0.4500	0.0260	3.5	15.39	89.27	2.27	2.69	0.5714	0.4001
8	0.4442	0.0389	4.0	15.55	90.49	2.21	2.66	0.6038	0.4325
9	0.4391	0.0539	4.5	15.68	91.53	2.16	2.65	0.6316	0.4616
10	0.4345	0.0704	5.0	15.80	92.44	2.12	2.66	0.6558	0.4879
11	0.4271	0.1057	6.0	16.00	94.03	2.05	2.68	0.6957	0.5334
12	0.4215	0.1413	7.0	16.18	95.43	1.94	2.70	0.7273	0.5715
13	0.4176	0.1745	8.0	16.36	96.81	1.80	2.69	0.7530	0.6039
14	0.4152	0.2039	9.0	16.55	98.20	1.60	2.65	0.7742	0.6317
15	0.4148	0.2287	10.0	16.78	99.79	1.27	2.58	0.7921	0.6558
16	0.4097	0.2487	11.0	16.79	100.02	1.42	2.47	0.8074	0.6770
17	0.3920	0.2640	12.0	16.24	96.94	2.81	2.31	0.8205	0.6957
18	0.3727	0.2751	13.0	15.59	93.21	4.51	2.09	0.8320	0.7124
19	0.3472	0.2825	14.0	14.65	87.73	7.07	1.77	0.8421	0.7274
20	0.3098	0.2865	15.0	13.17	78.99	11.50	1.02	0.8511	0.7408
21	0.2345	0.2878	16.0	10.04	60.30	21.07	2.65	0.8591	0.7530
22	0.1931	0.2867	17.0	8.32	50.04	56.90	4.09	0.8663	0.7641
23	0.1747	0.2837	18.0	7.57	45.58	10000.00	5.88	0.8727	0.7743
24	0.1719	0.2791	19.0	7.49	45.14	10000.00	8.35	0.8786	0.7836
25	0.1684	0.2732	20.0	7.37	44.47	10000.00	12.06	0.8840	0.7921
26	0.1635	0.2665	21.0	7.19	43.41	10000.00	18.29	0.8889	0.8001
27	0.1557	0.2590	22.0	6.87	41.54	10000.00	30.98	0.8934	0.8074
28	0.1409	0.2509	23.0	6.25	37.79	10000.00	70.68	0.8976	0.8142
29	0.1278	0.2425	24.0	5.69	34.42	10000.00	10000.00	0.9014	0.8206
30	0.1280	0.2339	25.0	5.71	34.60	10000.00	10000.00	0.9050	0.8265
31	0.1281	0.2252	26.0	5.73	34.77	10000.00	10000.00	0.9083	0.8321
32	0.1283	0.2164	27.0	5.76	34.92	10000.00	10000.00	0.9114	0.8373
33	0.1284	0.2077	28.0	5.78	35.07	10000.00	10000.00	0.9143	0.8422
34	0.1285	0.1992	29.0	5.80	35.21	10000.00	10000.00	0.9170	0.8468
35	0.1286	0.1907	30.0	5.81	35.33	10000.00	10000.00	0.9195	0.8511
36	0.1289	0.1521	35.0	5.89	35.86	10000.00	10000.00	0.9302	0.8696
37	0.1291	0.1201	40.0	5.94	36.27	10000.00	10000.00	0.9384	0.8840
38	0.1293	0.0946	45.0	5.99	36.58	10000.00	10000.00	0.9449	0.8956
39	0.1294	0.0746	50.0	6.02	36.84	10000.00	10000.00	0.9501	0.9050
40	0.1294	0.0593	55.0	6.05	37.05	10000.00	10000.00	0.9545	0.9129
41	0.1295	0.0477	60.0	6.07	37.22	10000.00	10000.00	0.9581	0.9196
42	0.1295	0.0344	70.0	6.11	37.50	10000.00	10000.00	0.9639	0.9303
43	0.1295	0.0340	80.0	6.13	37.71	10000.00	10000.00	0.9682	0.9384
44	0.1295	0.0484	90.0	6.15	37.87	10000.00	10000.00	0.9717	0.9449
45	0.1295	0.0798	100.0	6.17	38.00	10000.00	10000.00	0.9744	0.9501
46	0.1295	0.1283	110.0	6.18	38.11	10000.00	10000.00	0.9767	0.9545
47	0.1295	0.1915	120.0	6.19	38.20	10000.00	10000.00	0.9786	0.9581
48	0.1294	0.3402	140.0	6.21	38.34	10000.00	10000.00	0.9816	0.9639
49	0.1294	0.4770	160.0	6.22	38.45	10000.00	10000.00	0.9839	0.9682
50	0.1294	0.5651	180.0	6.23	38.53	10000.00	10000.00	0.9856	0.9717
51	0.1294	0.5932	200.0	6.24	38.60	10000.00	10000.00	0.9870	0.9744
52	0.1292	0.5697	220.0	6.24	38.60	10000.00	10000.00	0.9882	0.9767
53	0.1293	0.5120	240.0	6.25	38.70	10000.00	10000.00	0.9892	0.9786
54	0.1293	0.3596	280.0	6.26	38.77	10000.00	10000.00	0.9907	0.9816
55	0.1291	0.2235	320.0	6.26	38.77	10000.00	10000.00	0.9919	0.9839
56	0.1293	0.1289	360.0	6.27	38.87	10000.00	10000.00	0.9928	0.9856
57	0.1292	0.0710	400.0	6.27	38.87	10000.00	10000.00	0.9935	0.9871
58	0.1293	0.0381	440.0	6.28	38.93	10000.00	10000.00	0.9941	0.9882
59	0.1292	0.0201	480.0	6.28	38.93	10000.00	10000.00	0.9946	0.9892
60	0.1291	0.0105	520.0	6.28	38.93	10000.00	10000.00	0.9950	0.9900

p = 11.24 atm

JJ	R, Cal/sec	FZEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α*	XNUST, ξ*
1	0.0022	0.0000	0.5	0.02	0.10	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.03	0.12	10000.00	10000.00	0.2759	0.1601
3	0.6219	0.0008	1.5	7.87	38.39	5.04	6.31	0.3637	0.2223
4	0.6625	0.0032	2.0	8.75	43.19	3.05	3.57	0.4325	0.2759
5	0.6621	0.0080	2.5	9.06	44.97	2.57	2.99	0.4878	0.3227
6	0.6554	0.0156	3.0	9.25	46.04	2.37	2.77	0.5334	0.3637
7	0.6474	0.0260	3.5	9.38	46.81	2.27	2.69	0.5714	0.4001
8	0.6398	0.0389	4.0	9.49	47.42	2.21	2.66	0.6038	0.4325
9	0.6328	0.0539	4.5	9.57	47.93	2.16	2.65	0.6316	0.4616
10	0.6267	0.0704	5.0	9.65	48.38	2.12	2.66	0.6558	0.4879
11	0.6167	0.1057	6.0	9.79	49.17	2.05	2.68	0.6957	0.5334
12	0.6096	0.1413	7.0	9.92	49.90	1.94	2.70	0.7273	0.5715
13	0.6052	0.1745	8.0	10.05	50.63	1.80	2.69	0.7530	0.6039
14	0.6037	0.2039	9.0	10.19	51.45	1.60	2.65	0.7742	0.6317
15	0.6061	0.2287	10.0	10.39	52.51	1.27	2.58	0.7921	0.6558
16	0.5978	0.2487	11.0	10.38	52.51	1.42	2.47	0.8074	0.6770
17	0.5597	0.2640	12.0	9.82	49.76	2.81	2.31	0.8205	0.6957
18	0.5192	0.2751	13.0	9.20	46.65	4.51	2.09	0.8320	0.7124
19	0.4672	0.2825	14.0	8.35	42.38	7.07	1.77	0.8421	0.7274
20	0.3697	0.2865	15.0	6.66	33.81	11.50	1.02	0.8511	0.7408
21	0.3230	0.2878	16.0	5.86	29.77	21.07	2.65	0.8591	0.7530
22	0.2932	0.2867	17.0	5.35	27.22	56.90	4.09	0.8663	0.7641
23	0.2756	0.2837	18.0	5.06	25.75	10000.00	5.88	0.8727	0.7743
24	0.2692	0.2791	19.0	4.97	25.31	10000.00	8.35	0.8786	0.7836
25	0.2612	0.2732	20.0	4.84	24.70	10000.00	12.06	0.8840	0.7921
26	0.2503	0.2665	21.0	4.66	23.79	10000.00	18.29	0.8889	0.8001
27	0.2343	0.2590	22.0	4.38	22.38	10000.00	30.98	0.8934	0.8074
28	0.2101	0.2509	23.0	3.95	20.15	10000.00	70.68	0.8976	0.8142
29	0.1998	0.2425	24.0	3.76	19.24	10000.00	10000.00	0.9014	0.8206
30	0.2001	0.2339	25.0	3.78	19.35	10000.00	10000.00	0.9050	0.8265
31	0.2004	0.2252	26.0	3.80	19.45	10000.00	10000.00	0.9083	0.8321
32	0.2007	0.2164	27.0	3.82	19.54	10000.00	10000.00	0.9114	0.8373
33	0.2009	0.2077	28.0	3.83	19.63	10000.00	10000.00	0.9143	0.8422
34	0.2011	0.1992	29.0	3.84	19.71	10000.00	10000.00	0.9170	0.8468
35	0.2013	0.1907	30.0	3.86	19.78	10000.00	10000.00	0.9195	0.8511
36	0.2021	0.1521	35.0	3.91	20.10	10000.00	10000.00	0.9302	0.8696
37	0.2027	0.1201	40.0	3.95	20.34	10000.00	10000.00	0.9384	0.8840
38	0.2030	0.0946	45.0	3.98	20.53	10000.00	10000.00	0.9449	0.8956
39	0.2033	0.0746	50.0	4.01	20.68	10000.00	10000.00	0.9501	0.9050
40	0.2035	0.0593	55.0	4.03	20.80	10000.00	10000.00	0.9545	0.9129
41	0.2037	0.0477	60.0	4.05	20.91	10000.00	10000.00	0.9581	0.9196
42	0.2039	0.0344	70.0	4.07	21.07	10000.00	10000.00	0.9639	0.9303
43	0.2040	0.0340	80.0	4.09	21.19	10000.00	10000.00	0.9682	0.9384
44	0.2041	0.0484	90.0	4.11	21.29	10000.00	10000.00	0.9717	0.9449
45	0.2041	0.0798	100.0	4.12	21.37	10000.00	10000.00	0.9744	0.9501
46	0.2041	0.1283	110.0	4.13	21.43	10000.00	10000.00	0.9767	0.9545
47	0.2041	0.1915	120.0	4.14	21.48	10000.00	10000.00	0.9786	0.9581
48	0.2041	0.3402	140.0	4.15	21.57	10000.00	10000.00	0.9816	0.9639
49	0.2041	0.4770	160.0	4.16	21.63	10000.00	10000.00	0.9839	0.9682
50	0.2040	0.5651	180.0	4.16	21.68	10000.00	10000.00	0.9856	0.9717
51	0.2040	0.5932	200.0	4.17	21.72	10000.00	10000.00	0.9870	0.9744
52	0.2037	0.5697	220.0	4.17	21.72	10000.00	10000.00	0.9882	0.9767
53	0.2040	0.5120	240.0	4.18	21.78	10000.00	10000.00	0.9892	0.9785
54	0.2040	0.3596	280.0	4.18	21.82	10000.00	10000.00	0.9907	0.9816
55	0.2037	0.2235	320.0	4.18	21.82	10000.00	10000.00	0.9919	0.9839
56	0.2040	0.1289	360.0	4.19	21.88	10000.00	10000.00	0.9928	0.9856
57	0.2038	0.0710	400.0	4.19	21.88	10000.00	10000.00	0.9935	0.9871
58	0.2039	0.0381	440.0	4.20	21.91	10000.00	10000.00	0.9941	0.9882
59	0.2038	0.0201	480.0	4.20	21.91	10000.00	10000.00	0.9946	0.9892
60	0.2037	0.0105	520.0	4.20	21.91	10000.00	10000.00	0.9950	0.9900

p = 20 atm

JJ	R, Cm/sec	FZEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α^*	XNUST, ζ^*
1	0.0022	0.0000	0.5	0.01	0.03	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.01	0.04	10000.00	10000.00	0.2759	0.1601
3	0.7242	0.0008	1.5	3.86	16.13	5.04	6.31	0.3637	0.2223
4	0.9148	0.0032	2.0	5.09	21.81	3.05	3.57	0.4325	0.2759
5	0.9258	0.0080	2.5	5.34	22.95	2.57	2.99	0.4878	0.3227
6	0.9211	0.0156	3.0	5.48	23.57	2.37	2.77	0.5334	0.3637
7	0.9176	0.0260	3.5	5.57	23.98	2.27	2.69	0.5714	0.4001
8	0.9034	0.0389	4.0	5.64	24.29	2.21	2.66	0.6038	0.4325
9	0.8946	0.0539	4.5	5.70	24.54	2.16	2.65	0.6316	0.4616
10	0.8868	0.0704	5.0	5.75	24.76	2.12	2.66	0.6558	0.4879
11	0.8745	0.1057	6.0	5.85	25.17	2.05	2.68	0.6957	0.5334
12	0.8668	0.1413	7.0	5.94	25.56	1.94	2.70	0.7273	0.5715
13	0.8636	0.1745	8.0	6.04	25.99	1.80	2.69	0.7530	0.6039
14	0.8657	0.2039	9.0	6.16	26.50	1.60	2.65	0.7742	0.6317
15	0.8762	0.2287	10.0	6.33	27.22	1.27	2.58	0.7921	0.6558
16	0.8604	0.2487	11.0	6.29	27.07	1.42	2.47	0.8074	0.6770
17	0.7807	0.2640	12.0	5.77	24.83	2.81	2.31	0.8205	0.6957
18	0.6980	0.2751	13.0	5.21	22.41	4.51	2.09	0.8320	0.7124
19	0.5606	0.2825	14.0	4.22	18.14	7.07	1.77	0.8421	0.7274
20	0.5177	0.2865	15.0	3.93	16.89	11.50	1.02	0.8511	0.7408
21	0.4796	0.2878	16.0	3.67	15.76	21.07	2.65	0.8591	0.7530
22	0.4509	0.2867	17.0	3.47	14.92	56.90	4.09	0.8663	0.7641
23	0.4289	0.2837	18.0	3.32	14.28	10000.00	5.88	0.8727	0.7743
24	0.4147	0.2791	19.0	3.23	13.89	10000.00	8.35	0.8786	0.7836
25	0.3973	0.2732	20.0	3.10	13.37	10000.00	12.06	0.8840	0.7921
26	0.3751	0.2665	21.0	2.94	12.69	10000.00	18.29	0.8889	0.8001
27	0.3462	0.2590	22.0	2.73	11.76	10000.00	30.98	0.8934	0.8074
28	0.3154	0.2509	23.0	2.50	10.76	10000.00	70.68	0.8976	0.8142
29	0.3108	0.2425	24.0	2.47	10.64	10000.00	10000.00	0.9014	0.8206
30	0.3115	0.2339	25.0	2.48	10.71	10000.00	10000.00	0.9050	0.8265
31	0.3121	0.2252	26.0	2.49	10.77	10000.00	10000.00	0.9083	0.8321
32	0.3127	0.2164	27.0	2.51	10.83	10000.00	10000.00	0.9114	0.8373
33	0.3132	0.2077	28.0	2.52	10.88	10000.00	10000.00	0.9143	0.8422
34	0.3137	0.1992	29.0	2.53	10.93	10000.00	10000.00	0.9170	0.8468
35	0.3142	0.1907	30.0	2.54	10.97	10000.00	10000.00	0.9195	0.8511
36	0.3159	0.1521	35.0	2.58	11.16	10000.00	10000.00	0.9302	0.8696
37	0.3171	0.1201	40.0	2.61	11.30	10000.00	10000.00	0.9384	0.8840
38	0.3180	0.0946	45.0	2.63	11.41	10000.00	10000.00	0.9449	0.8956
39	0.3186	0.0746	50.0	2.65	11.50	10000.00	10000.00	0.9501	0.9050
40	0.3191	0.0593	55.0	2.66	11.58	10000.00	10000.00	0.9545	0.9129
41	0.3195	0.0477	60.0	2.67	11.64	10000.00	10000.00	0.9581	0.9196
42	0.3201	0.0344	70.0	2.69	11.74	10000.00	10000.00	0.9639	0.9303
43	0.3205	0.0340	80.0	2.71	11.81	10000.00	10000.00	0.9682	0.9384
44	0.3208	0.0484	90.0	2.72	11.87	10000.00	10000.00	0.9717	0.9449
45	0.3211	0.0798	100.0	2.73	11.91	10000.00	10000.00	0.9744	0.9501
46	0.3211	0.1283	110.0	2.74	11.95	10000.00	10000.00	0.9767	0.9545
47	0.3212	0.1915	120.0	2.74	11.98	10000.00	10000.00	0.9786	0.9581
48	0.3212	0.3402	140.0	2.75	12.03	10000.00	10000.00	0.9816	0.9639
49	0.3213	0.4770	160.0	2.76	12.07	10000.00	10000.00	0.9839	0.9682
50	0.3213	0.5651	180.0	2.76	12.10	10000.00	10000.00	0.9856	0.9717
51	0.3213	0.5932	200.0	2.77	12.12	10000.00	10000.00	0.9870	0.9744
52	0.3208	0.5697	220.0	2.77	12.12	10000.00	10000.00	0.9882	0.9767
53	0.3213	0.5120	240.0	2.77	12.16	10000.00	10000.00	0.9892	0.9786
54	0.3213	0.3596	280.0	2.78	12.18	10000.00	10000.00	0.9907	0.9816
55	0.3208	0.2235	320.0	2.78	12.18	10000.00	10000.00	0.9919	0.9839
56	0.3213	0.1289	360.0	2.78	12.22	10000.00	10000.00	0.9928	0.9856
57	0.3210	0.0710	400.0	2.78	12.22	10000.00	10000.00	0.9935	0.9871
58	0.3213	0.0381	440.0	2.79	12.24	10000.00	10000.00	0.9941	0.9882
59	0.3211	0.0201	480.0	2.79	12.24	10000.00	10000.00	0.9946	0.9892
60	0.3209	0.0105	520.0	2.78	12.24	10000.00	10000.00	0.9950	0.9900

p = 35.40 atm

JJ	R, cm/sec	FZEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	\STPD, μ	XSTARD, μ	ALFAST, α*	XMUST, ζ*
1	0.0022	0.0000	0.5	0.00	0.01	10000.00	10000.00	0.1600	0.0870
2	C.0025	0.0001	1.0	0.01	0.02	10000.00	10000.00	0.2759	0.1601
3	C.8763	0.0008	1.5	1.98	7.14	5.04	6.31	0.3637	0.2223
4	1.0518	0.0032	2.0	2.49	9.14	3.05	3.57	0.4325	0.2759
5	1.1145	0.0080	2.5	2.73	10.11	2.57	2.99	0.4878	0.3227
6	1.2464	0.0156	3.0	3.15	11.76	2.37	2.77	0.5334	0.3637
7	1.2400	0.0260	3.5	3.22	11.99	2.27	2.69	0.5714	0.4001
8	1.2307	0.0389	4.0	3.26	12.16	2.21	2.66	0.6038	0.4325
9	1.2212	0.0539	4.5	3.31	12.29	2.16	2.65	0.6316	0.4616
10	1.2126	0.0704	5.0	3.34	12.40	2.12	2.66	0.6558	0.4879
11	1.1998	0.1057	6.0	3.41	12.61	2.05	2.68	0.6957	0.5334
12	1.1940	0.1413	7.0	3.47	12.84	1.94	2.70	0.7273	0.5715
13	1.1961	0.1745	8.0	3.55	13.10	1.80	2.69	0.7530	0.6039
14	1.2081	0.2039	9.0	3.65	13.45	1.60	2.65	0.7742	0.6317
15	1.2377	0.2287	10.0	3.80	13.97	1.27	2.58	0.7921	0.6558
16	1.2089	0.2487	11.0	3.75	13.80	1.42	2.47	0.8074	0.6770
17	0.9459	0.2640	12.0	2.97	10.87	2.81	2.31	0.8205	0.6957
18	0.8392	0.2751	13.0	2.66	9.73	4.51	2.09	0.8320	0.7124
19	C.7910	0.2825	14.0	2.53	9.24	7.07	1.77	0.8421	0.7274
20	0.7721	0.2865	15.0	2.49	9.09	11.50	1.02	0.8511	0.7408
21	0.7233	0.2878	16.0	2.35	8.57	21.07	2.65	0.8591	0.7530
22	C.6846	0.2867	17.0	2.24	8.16	56.90	4.09	0.8663	0.7641
23	0.6499	0.2837	18.0	2.14	7.79	10000.00	5.88	0.8727	0.7743
24	0.6200	0.2791	19.0	2.05	7.47	10000.00	8.35	0.8786	0.7836
25	C.5856	0.2732	20.0	1.94	7.09	10000.00	12.06	0.8840	0.7921
26	0.5458	0.2665	21.0	1.82	6.64	10000.00	18.29	0.8889	0.8001
27	0.5034	0.2590	22.0	1.68	6.15	10000.00	30.98	0.8934	0.8074
28	0.4766	0.2509	23.0	1.60	5.84	10000.00	70.68	0.8976	0.8142
29	0.4770	0.2425	24.0	1.61	5.87	10000.00	10000.00	0.9014	0.8206
30	0.4785	0.2339	25.0	1.62	5.91	10000.00	10000.00	0.9050	0.8265
31	0.4798	0.2252	26.0	1.63	5.95	10000.00	10000.00	0.9083	0.8321
32	0.4810	0.2164	27.0	1.64	5.98	10000.00	10000.00	0.9114	0.8373
33	C.4821	0.2077	28.0	1.64	6.01	10000.00	10000.00	0.9143	0.8422
34	0.4831	0.1992	29.0	1.65	6.04	10000.00	10000.00	0.9170	0.8468
35	0.4841	0.1907	30.0	1.66	6.07	10000.00	10000.00	0.9195	0.8511
36	0.4878	0.1521	35.0	1.69	6.18	10000.00	10000.00	0.9302	0.8696
37	0.4904	0.1201	40.0	1.71	6.27	10000.00	10000.00	0.9384	0.8840
38	C.4923	C.0946	45.0	1.73	6.34	10000.00	10000.00	0.9449	0.8956
39	0.4938	0.0746	50.0	1.74	6.39	10000.00	10000.00	0.9501	0.9050
40	0.4949	0.0593	55.0	1.75	6.44	10000.00	10000.00	0.9545	0.9129
41	C.4958	0.0477	60.0	1.76	6.47	10000.00	10000.00	0.9581	0.9196
42	0.4972	0.0344	70.0	1.78	6.53	10000.00	10000.00	0.9639	0.9303
43	0.4982	0.0340	80.0	1.79	6.58	10000.00	10000.00	0.9682	0.9384
44	C.4989	0.0484	90.0	1.80	6.61	10000.00	10000.00	0.9717	0.9449
45	0.4995	0.0798	100.0	1.80	6.64	10000.00	10000.00	0.9744	0.9501
46	0.4999	0.1283	110.0	1.81	6.66	10000.00	10000.00	0.9767	0.9545
47	0.5003	0.1915	120.0	1.81	6.68	10000.00	10000.00	0.9786	0.9581
48	0.5005	0.3402	140.0	1.82	6.71	10000.00	10000.00	0.9816	0.9639
49	C.5007	0.4770	160.0	1.82	6.73	10000.00	10000.00	0.9839	0.9682
50	0.5008	0.5651	180.0	1.83	6.75	10000.00	10000.00	0.9856	0.9717
51	0.5009	0.5932	200.0	1.83	6.76	10000.00	10000.00	0.9870	0.9744
52	C.5001	0.5697	220.0	1.83	6.76	10000.00	10000.00	0.9882	0.9767
53	0.5010	0.5120	240.0	1.84	6.78	10000.00	10000.00	0.9892	0.9786
54	0.5011	0.3596	280.0	1.84	6.80	10000.00	10000.00	0.9907	0.9816
55	C.5004	0.2235	320.0	1.84	6.80	10000.00	10000.00	0.9919	0.9639
56	0.5013	0.1289	360.0	1.84	6.82	10000.00	10000.00	0.9928	0.9856
57	C.5008	0.0710	400.0	1.84	6.82	10000.00	10000.00	0.9935	0.9871
58	C.5013	0.0381	440.0	1.85	6.83	10000.00	10000.00	0.9941	0.9882
59	0.5010	0.0201	480.0	1.85	6.83	10000.00	10000.00	0.9946	0.9892
60	C.5007	0.0105	520.0	1.85	6.83	10000.00	10000.00	0.9950	0.9900

$p = 63.40$ atm

JJ	R, cm/sec	FZEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α^*	XNUST, ζ^*
1	C.0022	0.0000	0.5	0.00	0.00	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.00	0.01	10000.00	10000.00	0.2759	0.1601
3	1.0707	0.0008	1.5	1.01	3.13	5.04	6.31	0.3637	0.2223
4	1.3090	0.0032	2.0	1.29	4.10	3.05	3.57	0.4325	0.2759
5	1.3722	0.0080	2.5	1.40	4.48	2.57	2.99	0.4878	0.3227
6	1.3923	0.0156	3.0	1.47	4.68	2.37	2.77	0.5334	0.3637
7	1.3967	0.0260	3.5	1.51	4.81	2.27	2.69	0.5714	0.4001
8	1.3946	0.0389	4.0	1.54	4.91	2.21	2.66	0.6038	0.4325
9	1.3903	0.0539	4.5	1.57	4.98	2.16	2.65	0.6316	0.4616
10	1.3859	0.0704	5.0	1.59	5.05	2.12	2.66	0.6558	0.4879
11	1.3804	0.1057	6.0	1.64	5.16	2.05	2.68	0.6957	0.5334
12	1.3835	0.1413	7.0	1.68	5.29	1.94	2.70	0.7273	0.5715
13	1.4002	0.1745	8.0	1.74	5.45	1.80	2.69	0.7530	0.6039
14	1.4422	0.2039	9.0	1.82	5.71	1.60	2.65	0.7742	0.6317
15	1.7087	0.2287	10.0	2.19	6.88	1.27	2.58	0.7921	0.6558
16	1.4827	0.2487	11.0	1.92	6.01	1.42	2.47	0.8074	0.6770
17	1.2550	0.2640	12.0	1.64	5.12	2.81	2.31	0.8205	0.6957
18	1.1944	0.2751	13.0	1.58	4.91	4.51	2.09	0.8320	0.7124
19	1.1709	0.2825	14.0	1.56	4.85	7.07	1.77	0.8421	0.7274
20	1.1819	0.2865	15.0	1.59	4.93	11.50	1.02	0.8511	0.7408
21	1.0916	0.2878	16.0	1.48	4.58	21.07	2.65	0.8591	0.7530
22	1.0248	0.2867	17.0	1.40	4.32	56.90	4.09	0.8663	0.7641
23	C.9624	0.2837	18.0	1.32	4.08	10000.00	5.88	0.8727	0.7743
24	0.9044	0.2791	19.0	1.25	3.85	10000.00	8.35	0.8786	0.7836
25	0.8439	0.2732	20.0	1.17	3.61	10000.00	12.06	0.8840	0.7921
26	0.7841	0.2665	21.0	1.09	3.36	10000.00	18.29	0.8889	0.8001
27	0.7374	0.2590	22.0	1.03	3.18	10000.00	30.98	0.8934	0.8074
28	0.7258	0.2509	23.0	1.02	3.14	10000.00	70.68	0.8976	0.8142
29	0.7291	0.2425	24.0	1.03	3.16	10000.00	10000.00	0.9014	0.8206
30	0.7322	0.2339	25.0	1.03	3.19	10000.00	10000.00	0.9050	0.8265
31	C.7349	0.2252	26.0	1.04	3.21	10000.00	10000.00	0.9083	0.8321
32	0.7375	0.2164	27.0	1.05	3.23	10000.00	10000.00	0.9114	0.8373
33	0.7398	0.2077	28.0	1.05	3.25	10000.00	10000.00	0.9143	0.8422
34	0.7419	0.1992	29.0	1.06	3.27	10000.00	10000.00	0.9170	0.8468
35	0.7439	0.1907	30.0	1.06	3.28	10000.00	10000.00	0.9195	0.8511
36	C.7517	0.1521	35.0	1.09	3.35	10000.00	10000.00	0.9302	0.8696
37	0.7572	0.1201	40.0	1.10	3.40	10000.00	10000.00	0.9384	0.8840
38	0.7614	0.0946	45.0	1.11	3.44	10000.00	10000.00	0.9449	0.8956
39	0.7645	0.0746	50.0	1.13	3.48	10000.00	10000.00	0.9501	0.9050
40	0.7671	0.0593	55.0	1.13	3.50	10000.00	10000.00	0.9545	0.9129
41	0.7691	0.0477	60.0	1.14	3.52	10000.00	10000.00	0.9581	0.9196
42	C.7723	0.0344	70.0	1.15	3.56	10000.00	10000.00	0.9639	0.9303
43	0.7745	0.0340	80.0	1.16	3.59	10000.00	10000.00	0.9682	0.9384
44	0.7762	0.0484	90.0	1.17	3.61	10000.00	10000.00	0.9717	0.9449
45	0.7775	0.0798	100.0	1.17	3.62	10000.00	10000.00	0.9744	0.9501
46	0.7785	0.1293	110.0	1.18	3.64	10000.00	10000.00	0.9767	0.9545
47	C.7794	0.1915	120.0	1.18	3.65	10000.00	10000.00	0.9786	0.9581
48	0.7806	0.3402	140.0	1.18	3.67	10000.00	10000.00	0.9816	0.9639
49	0.7813	0.4770	160.0	1.19	3.68	10000.00	10000.00	0.9839	0.9682
50	C.7817	0.5651	180.0	1.19	3.69	10000.00	10000.00	0.9856	0.9717
51	0.7820	0.5932	200.0	1.19	3.70	10000.00	10000.00	0.9870	0.9744
52	0.7808	0.5697	220.0	1.19	3.70	10000.00	10000.00	0.9882	0.9767
53	C.7824	0.5120	240.0	1.20	3.71	10000.00	10000.00	0.9892	0.9786
54	0.7827	0.3596	280.0	1.20	3.72	10000.00	10000.00	0.9907	0.9816
55	C.7815	0.2235	320.0	1.20	3.72	10000.00	10000.00	0.9919	0.9839
56	C.7831	0.1289	360.0	1.20	3.73	10000.00	10000.00	0.9928	0.9856
57	0.7824	0.0710	400.0	1.20	3.73	10000.00	10000.00	0.9935	0.9871
58	C.7833	0.0381	440.0	1.20	3.74	10000.00	10000.00	0.9941	0.9882
59	C.7828	0.0201	480.0	1.20	3.74	10000.00	10000.00	0.9946	0.9892
60	0.7824	0.0105	520.0	1.20	3.74	10000.00	10000.00	0.9950	0.9900

p = 112.40 atm.

JJ	R, cm/sec	FZEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α*	XNUST, ζ*
1	C.0022	0.0000	0.5	0.00	0.00	10000.00	10000.00	0.1600	0.0870
2	C.0025	0.0001	1.0	0.00	0.00	10000.00	10000.00	0.2759	0.1601
3	1.2389	0.0008	1.5	0.50	1.32	5.04	6.37	0.3637	0.2223
4	1.6207	0.0032	2.0	0.68	1.87	3.05	3.57	0.4325	0.2759
5	1.7298	0.0080	2.5	0.75	2.08	2.57	2.99	0.4878	0.3227
6	1.7707	0.0156	3.0	0.79	2.19	2.37	2.77	0.5334	0.3637
7	1.7864	0.0260	3.5	0.82	2.26	2.27	2.69	0.5714	0.4001
8	1.7914	0.0389	4.0	0.84	2.31	2.21	2.66	0.6038	0.4325
9	1.7917	0.0539	4.5	0.86	2.35	2.16	2.65	0.6316	0.4616
10	1.7903	0.0704	5.0	0.87	2.39	2.12	2.66	0.6558	0.4879
11	1.7881	0.1057	6.0	0.90	2.44	2.05	2.68	0.6957	0.5334
12	1.7911	0.1413	7.0	0.92	2.50	1.94	2.70	0.7273	0.5715
13	1.8036	0.1745	8.0	0.95	2.56	1.80	2.69	0.7530	0.6039
14	1.8331	0.2039	9.0	0.98	2.64	1.60	2.65	0.7742	0.6317
15	1.9104	0.2287	10.0	1.04	2.78	1.27	2.58	0.7921	0.6558
16	1.8713	0.2487	11.0	1.03	2.75	1.42	2.47	0.8074	0.6770
17	1.7378	0.2640	12.0	0.96	2.57	2.81	2.31	0.8205	0.6957
18	1.7099	0.2751	13.0	0.96	2.55	4.51	2.09	0.8320	0.7124
19	1.7154	0.2825	14.0	0.97	2.57	7.07	1.77	0.8421	0.7274
20	1.7840	0.2865	15.0	1.02	2.70	11.50	1.02	0.8511	0.7408
21	1.5957	0.2878	16.0	0.92	2.42	21.07	2.65	0.8591	0.7530
22	1.4728	0.2867	17.0	0.85	2.24	56.90	4.09	0.8663	0.7641
23	1.3637	0.2837	18.0	0.79	2.08	10000.00	5.88	0.8727	0.7743
24	1.2664	0.2791	19.0	0.74	1.94	10000.00	8.35	0.8786	0.7836
25	1.1776	0.2732	20.0	0.69	1.81	10000.00	12.06	0.8840	0.7921
26	1.1084	0.2665	21.0	0.65	1.71	10000.00	18.29	0.8889	0.8001
27	1.0782	0.2590	22.0	0.64	1.67	10000.00	30.98	0.8934	0.8074
28	1.0814	0.2509	23.0	0.64	1.68	10000.00	70.68	0.8976	0.8142
29	1.0880	0.2425	24.0	0.65	1.70	10000.00	10000.00	0.9014	0.8206
30	1.0940	0.2339	25.0	0.65	1.71	10000.00	10000.00	0.9050	0.8265
31	1.0995	0.2252	26.0	0.66	1.72	10000.00	10000.00	0.9083	0.8321
32	1.1045	0.2164	27.0	0.66	1.74	10000.00	10000.00	0.9114	0.8373
33	1.1092	0.2077	28.0	0.67	1.75	10000.00	10000.00	0.9143	0.8422
34	1.1135	0.1992	29.0	0.67	1.76	10000.00	10000.00	0.9170	0.8468
35	1.1174	0.1907	30.0	0.68	1.77	10000.00	10000.00	0.9195	0.8511
36	1.1335	0.1521	35.0	0.69	1.81	10000.00	10000.00	0.9302	0.8696
37	1.1450	0.1201	40.0	0.71	1.84	10000.00	10000.00	0.9384	0.8840
38	1.1535	0.0946	45.0	0.72	1.87	10000.00	10000.00	0.9449	0.8956
39	1.1601	0.0746	50.0	0.72	1.89	10000.00	10000.00	0.9501	0.9050
40	1.1655	0.0593	55.0	0.73	1.90	10000.00	10000.00	0.9545	0.9129
41	1.1698	0.0477	60.0	0.73	1.92	10000.00	10000.00	0.9581	0.9196
42	1.1765	0.0344	70.0	0.74	1.94	10000.00	10000.00	0.9639	0.9303
43	1.1813	0.0340	80.0	0.75	1.96	10000.00	10000.00	0.9682	0.9384
44	1.1850	0.0484	90.0	0.75	1.97	10000.00	10000.00	0.9717	0.9449
45	1.1878	0.0798	100.0	0.76	1.98	10000.00	10000.00	0.9744	0.9501
46	1.1901	0.1283	110.0	0.76	1.99	10000.00	10000.00	0.9767	0.9545
47	1.1920	0.1915	120.0	0.76	1.99	10000.00	10000.00	0.9786	0.9581
48	1.1948	0.3402	140.0	0.77	2.00	10000.00	10000.00	0.9816	0.9639
49	1.1969	0.4770	160.0	0.77	2.01	10000.00	10000.00	0.9839	0.9682
50	1.1984	0.5651	180.0	0.77	2.02	10000.00	10000.00	0.9856	0.9717
51	1.1992	0.5932	200.0	0.77	2.02	10000.00	10000.00	0.9870	0.9744
52	1.1973	0.5697	220.0	0.77	2.02	10000.00	10000.00	0.9882	0.9767
53	1.2003	0.5120	240.0	0.78	2.03	10000.00	10000.00	0.9892	0.9786
54	1.2010	0.3596	280.0	0.78	2.04	10000.00	10000.00	0.9907	0.9816
55	1.1992	0.2235	320.0	0.78	2.04	10000.00	10000.00	0.9919	0.9839
56	1.2020	0.1289	360.0	0.78	2.04	10000.00	10000.00	0.9928	0.9856
57	1.2009	0.0710	400.0	0.78	2.04	10000.00	10000.00	0.9935	0.9871
58	1.2027	0.0381	440.0	0.78	2.05	10000.00	10000.00	0.9941	0.9882
59	1.2019	0.0201	480.0	0.78	2.05	10000.00	10000.00	0.9946	0.9892
60	1.2012	0.0105	520.0	0.78	2.05	10000.00	10000.00	0.9950	0.9900

$p = 200$ atm.

JJ	R, cm/sec	FZEROP	DZERO, μ	XSTPF, μ	XSTAP, μ	XSTPD, μ	XSTARD, μ	ALFAST, α^*	XNUST, ζ^*
1	0.0022	0.0000	0.5	0.00	0.00	10000.00	10000.00	0.1600	0.0870
2	0.0025	0.0001	1.0	0.00	0.00	10000.00	10000.00	0.2759	0.1601
3	1.3484	0.0008	1.5	0.23	0.52	5.04	6.31	0.3637	0.2223
4	1.9047	0.0032	2.0	0.34	0.80	3.05	3.57	0.4325	0.2759
5	2.0972	0.0080	2.5	0.38	0.92	2.57	2.99	0.4878	0.3227
6	2.1844	0.0156	3.0	0.41	0.99	2.37	2.77	0.5334	0.3637
7	2.2296	0.0260	3.5	0.43	1.03	2.27	2.69	0.5714	0.4001
8	2.2553	0.0389	4.0	0.45	1.06	2.21	2.66	0.6038	0.4325
9	2.2711	0.0539	4.5	0.46	1.09	2.16	2.65	0.6316	0.4616
10	7.2821	0.0704	5.0	0.47	1.11	2.12	2.66	0.6558	0.4879
11	2.2989	0.1057	6.0	0.49	1.14	2.05	2.68	0.6957	0.5334
12	2.3168	0.1413	7.0	0.50	1.17	1.94	2.70	0.7273	0.5715
13	2.3413	0.1745	8.0	0.52	1.20	1.80	2.69	0.7530	0.6039
14	2.3787	0.2039	9.0	0.54	1.24	1.60	2.65	0.7742	0.6317
15	2.4498	0.2287	10.0	0.56	1.29	1.27	2.58	0.7921	0.6558
16	2.4478	0.2487	11.0	0.57	1.30	1.42	2.47	0.8074	0.6770
17	2.3815	0.2640	12.0	0.56	1.27	2.81	2.31	0.8205	0.6957
18	2.3955	0.2751	13.0	0.57	1.29	4.51	2.09	0.8320	0.7124
19	2.4508	0.2825	14.0	0.58	1.33	7.07	1.77	0.8421	0.7274
20	2.6385	0.2865	15.0	0.63	1.44	11.50	1.02	0.8511	0.7408
21	2.2505	0.2878	16.0	0.54	1.23	21.07	2.65	0.8591	0.7530
22	2.0339	0.2867	17.0	0.49	1.11	56.90	4.09	0.8663	0.7641
23	1.8604	0.2837	18.0	0.46	1.02	10000.00	5.88	0.8727	0.7743
24	1.7207	0.2791	19.0	0.42	0.95	10000.00	8.35	0.8786	0.7836
25	1.6172	0.2732	20.0	0.40	0.89	10000.00	12.06	0.8840	0.7921
26	1.5658	0.2665	21.0	0.39	0.86	10000.00	18.29	0.8889	0.8001
27	1.5607	0.2590	22.0	0.39	0.86	10000.00	30.98	0.8934	0.8074
28	1.5787	0.2509	23.0	0.39	0.88	10000.00	70.68	0.8976	0.8142
29	1.5915	0.2425	24.0	0.40	0.89	10000.00	10000.00	0.9014	0.8206
30	1.6032	0.2339	25.0	0.40	0.90	10000.00	10000.00	0.9050	0.8265
31	1.6139	0.2252	26.0	0.41	0.90	10000.00	10000.00	0.9083	0.8321
32	1.6237	0.2164	27.0	0.41	0.91	10000.00	10000.00	0.9114	0.8373
33	1.6328	0.2077	28.0	0.41	0.92	10000.00	10000.00	0.9143	0.8422
34	1.6412	0.1992	29.0	0.42	0.93	10000.00	10000.00	0.9170	0.8468
35	1.6490	0.1907	30.0	0.42	0.93	10000.00	10000.00	0.9195	0.8511
36	1.6809	0.1521	35.0	0.43	0.96	10000.00	10000.00	0.9302	0.8696
37	1.7042	0.1201	40.0	0.44	0.98	10000.00	10000.00	0.9384	0.8840
38	1.7220	0.0946	45.0	0.45	0.99	10000.00	10000.00	0.9449	0.8956
39	1.7356	0.0746	50.0	0.46	1.01	10000.00	10000.00	0.9501	0.9050
40	1.7464	0.0593	55.0	0.46	1.02	10000.00	10000.00	0.9545	0.9129
41	1.7554	0.0477	60.0	0.46	1.02	10000.00	10000.00	0.9581	0.9196
42	1.7691	0.0344	70.0	0.47	1.04	10000.00	10000.00	0.9639	0.9303
43	1.7792	0.0340	80.0	0.48	1.05	10000.00	10000.00	0.9682	0.9384
44	1.7869	0.0484	90.0	0.48	1.05	10000.00	10000.00	0.9717	0.9449
45	1.7930	0.0798	100.0	0.48	1.06	10000.00	10000.00	0.9744	0.9501
46	1.7979	0.1283	110.0	0.48	1.07	10000.00	10000.00	0.9767	0.9545
47	1.8019	0.1915	120.0	0.49	1.07	10000.00	10000.00	0.9786	0.9581
48	1.8080	0.3402	140.0	0.49	1.08	10000.00	10000.00	0.9816	0.9639
49	1.8125	0.4770	160.0	0.49	1.08	10000.00	10000.00	0.9839	0.9682
50	1.8159	0.5651	180.0	0.49	1.08	10000.00	10000.00	0.9856	0.9717
51	1.8185	0.5932	200.0	0.50	1.09	10000.00	10000.00	0.9870	0.9744
52	1.8164	0.5697	220.0	0.50	1.09	10000.00	10000.00	0.9882	0.9767
53	1.8219	0.5120	240.0	0.50	1.09	10000.00	10000.00	0.9892	0.9786
54	1.8238	0.3596	280.0	0.50	1.10	10000.00	10000.00	0.9907	0.9816
55	1.8210	0.2235	320.0	0.50	1.10	10000.00	10000.00	0.9919	0.9839
56	1.8261	0.1289	360.0	0.50	1.10	10000.00	10000.00	0.9928	0.9856
57	1.8244	0.0710	400.0	0.50	1.10	10000.00	10000.00	0.9935	0.9871
58	1.8276	0.0381	440.0	0.50	1.10	10000.00	10000.00	0.9941	0.9882
59	1.8264	0.0201	480.0	0.50	1.10	10000.00	10000.00	0.9946	0.9892
60	1.8254	0.0105	520.0	0.50	1.10	10000.00	10000.00	0.9950	0.9900

PARABOLIC FLAME ASSUMED

PROPELLANT DATA IS
WT. PERCENT OXID. = 90.0
PROP. DENSITY = 0.0 BINDER DENSITY = 0.98 OXID. DENSITY = 1.95
QFUEL = 25.0 TF(DEG K) = 2028. MOL WT = 20.87 PRI MOL WT = 28.00
DIFF PARAM = 1000.0000 ST RAT = 16.50 PRI ST RAT = 8.30

OXIDIZER IGNITION AND BURNING DATA IS
CIGN = 190.0 POWIGN = 0.721 POWD = 0.8 LATENT HEAT = -110.0

ACTIVATION ENERGIES AND RATE FACTORS ARE
EF = 15000. E OX = 26000. AF = 0.270D 04 A OX = 0.300D 06
ORDER, PF = 1.500 RT CON, PF = 0.250D 02 ORDER, LP = 1.800 RT CON, LP = 0.231D 01
ORDER, HP = 1.800 RT CON, HP = 0.231D 01

FLAME PROPERTIES ARE
OXID. FLM TEMP = 1400.0 GAS CONDUCT = 0.00020 CP(AVE) = 0.3000
AV FLM HT FACT = 0.3000

PROPELLANT INITIAL TEMP IS 21.1 DEG CENTIGRADE m (exponent in Eq. 19) = 2

EXPONENT FOR DIFFUSION PRESSURE DEPENDENCE IS 1.000

PRES ATMS	PRES PSIA	3R CM/SEC	BR IN/SEC
2.00	29.4	0.1006	0.0396
3.54	52.0	0.1515	0.0597
6.34	93.2	0.2287	0.0900
11.24	165.2	0.3405	0.1341
20.00	294.0	0.5047	0.1987
35.40	520.4	0.7357	0.2896
63.40	932.0	1.0400	0.4095
112.40	1652.3	1.4896	0.5860
200.00	2940.0	2.1296	0.8384

Appendix B

HYDRAULIC ANALOGY

The analogy between one-dimensional, nonsteady flows of inviscid gases and inviscid liquids with free surfaces and between two-dimensional, steady flows of inviscid gases and inviscid liquids with free surfaces is well documented in the literature[22]. As one might expect in this situation, the analogy also extends to two-dimensional, nonsteady flows. However, although this analogy has been exploited in several studies,[22] no explicit derivation of the analogy for the nonsteady, two-dimensional situation has apparently been presented.* The object of this appendix is to present a derivation for this situation.

For nonsteady, two-dimensional, irrotational flow of a perfect gas the governing equations are[24]

$$\partial\rho/\partial t + \partial\rho u/\partial x + \partial\rho v/\partial y = 0 \tag{B-1}$$

$$\partial u/\partial t + u\,\partial u/\partial x + v\,\partial u/\partial y + \rho^{-1}\,\partial p/\partial x = 0 \tag{B-2}$$

$$\partial v/\partial t + u\,\partial v/\partial x + v\,\partial v/\partial y + \rho^{-1}\,\partial p/\partial y = 0 \tag{B-3}$$

$$p/p_o = (\rho/\rho_o)^{\gamma} \tag{B-4}$$

Employing a_o, ρ_o, p_o, l_g, t_g as reference dimensions and Eq. B-4 to eliminate ρ from Eqs. B-2 and B-3 yields the non-dimensional equations

$$\partial\rho^+ u^+/\partial x^+ + \partial\rho^+ v^+/\partial y^+ + (l_g/(a_o t_g))\,\partial p^+/\partial t^+ \tag{B-5}$$

$$[l_g/(a_o t_g)]\,\partial u^+/\partial t + u^+\,\partial u^+/\partial x^+ + v^+\,\partial u^+/\partial y^+ + [\partial (p^+)^{\frac{\gamma-1}{\gamma}}/\partial x^+]/(\gamma-1) = 0 \tag{B-6}$$

$$[l_g/(a_o t_g)]\,\partial v^+/\partial t^+ + u^+\,\partial v^+/\partial x^+ + v^+\,\partial v^+/\partial y^+ + [\partial (p^+)^{\frac{\gamma-1}{\gamma}}/\partial y^+]/(\gamma-1) = 0 \tag{B-7}$$

A three dimensional, nonsteady flow of inviscid liquid over a planar surface perpendicular to the gravity vector g is governed by the equations[24]

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*Loh[23] indicates in a footnote that the analogy extends to this case.

$$\partial u/\partial x + \partial v/\partial y + \partial w/\partial z = 0 \tag{B-8}$$

$$D_u/D_t + \rho^{-1} \partial p/\partial x = 0 \tag{B-9}$$

$$D_v/D_t + \rho^{-1} \partial p/\partial y = 0 \tag{B-10}$$

$$D_w/D_t + \rho^{-1} \partial p/\partial z + g = 0 \tag{B-11}$$

Assuming that vertical water accelerations are small compared to g Eq. B-11 becomes

$$\partial p/\partial z = -\rho g \tag{B-12}$$

Integration yields

$$p(x, y, z, t) = \rho g \int_h^z dz + p(x, y, h, t) \tag{B-13}$$

where $h(x, y, t)$ is the depth of the water. However, since only pressure differences are encountered in Eq. (B-9) to (B-11) and since $p(x, y, h, t) =$ constant, that constant can be set to zero without loss of generality. Consequently,

$$p(x, y, z, t) = \rho g (h-z) \tag{B-14}$$

and

$$\rho^{-1} \partial p/\partial x = g \partial h/\partial x \tag{B-15}$$

$$\rho^{-1} \partial p/\partial y = g \partial h/\partial y \tag{B-16}$$

Analysis is directed at inviscid motion. Assume $u = u(x, y, t)$ and $v = v(x, y, t)$. Therefore, terms containing w are eliminated from Eqs. (B-9) and (B-10). However, since $w = w(z), \partial w/\partial z \neq 0$. Formally integrating Eq. (B-8) from z=0 to z=h yields (after application of Liebnitz's rule[21])and the above assumption

$$\partial hu/\partial x + \partial hv/\partial y + w(x, y, h, t) = u(x, y, h, t) \partial h/\partial x + v(x, y, h, t) \partial h/\partial y \tag{B-17}$$

Since $w(x, y, h, t) = \partial h/\partial t + u(x, y, h, t) \partial h/\partial x + v(x, y, h, t) \partial h/\partial y$, Eq. (B-17)

becomes

$$\partial h/\partial t + \partial hu/\partial x + \partial hv/\partial y = 0 \tag{B-18}$$

Nondimensionalizing Eqs. B-9, B-10, and B-18 with reference dimensions h_o, gh_o, l_w, and t_w yields the non-dimensional hydraulic equations

$$\partial h^+u^+/\partial x^+ + \partial h^+v^+/\partial y^+ + [l_w/(\sqrt{gh_o}\, t_w)]\, \partial h^+/\partial t^+ = 0 \quad \text{(B-19)}$$

$$[l_w/(\sqrt{gh_o}\, l_w)]\, \partial u^+/\partial t^+ + u^+ \partial u^+/\partial x^+ + v^+ \partial u^+/\partial y^+ + \partial h^+/\partial x^+ = 0 \quad \text{(B-20)}$$

$$[l_w/(\sqrt{gh_o}\, l_w)]\, \partial v^+/\partial t^+ + u^+ \partial v^+/\partial x^+ + v^+ \partial v^+/\partial y^+ + \partial h^+/\partial y^+ = 0 \quad \text{(B-21)}$$

Comparison of Eqs. (B-5) to (B-7) with Eqs. (B-19) to (B-21) shows that when $\gamma = 2$ and $l_w/(\sqrt{gh_o}\, t_w) = l_g/(a_o t_g)$ the non-dimensional equations are equivalent if $h^+ = \rho^+$. Consequently, under these conditions an analogy exists between the gas and free surface liquid flows. In this analogy $h^+ = \sqrt{p^+}$ [or $p^+ = (h^+)^2$], $a = \sqrt{gh}$, $h^+ = \rho^+$, $u_w^+ = u_g^+$, and $v_v^+ = v_g^+$. For conditions where $0(l_w) \sim 0(l_g), 0(t_w) < 0(t_g)$. In other words, time is effectively slowed in the analogy. This means that transient phenomena can often be studied visually in the hydraulic analogy. It is this fact that makes the analogy valuable for nonsteady situations.

It has been shown that an analogy exists between irrotational flow of gas with $\gamma = 2$ and irrotational flow of liquid over a horizontal surface. Flows in nature are not irrotational. Therefore, of what practical value is this analogy? First, numerous experiments[22] have demonstrated excellent agreement with theory for simple flows. Second, there seems to be no question that the analogy provides a relatively simple way to obtain information on complex flow situations.[22]

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Monodisperse BDP combustion model was extended to nonmetallized propellants with mixed, polydisperse oxidizers by embedding monodisperse model in statistical framework including mixture ratio effects. Basically, polydisperse propellant is "disassembled and rearranged" to form sequence of monodisperse pseudo-propellants whose rates are computed via monodisperse model. Reassembly provides real propellant's burning rate. Approach provides information pertaining to distribution of regression rates and surface structure among different size oxidizer particles Preliminary results suggest that significant factor in rate increases wrought by

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introduction of small oxidizer modes is mixture ratio alterations in larger modes. Hydraulic T-burner analog was constructed and employed to visualize vent flow phenomena. Studies showed that flow enters vent with axial momentum and that momentum is partially transformed to vent into Karman vortex sheet. Fact that flow enters vent with axial momentum invalidates boundary condition of Culick analysis for flow turning gain; "correct" boundary condition leads to null vent gain. Experimental facts consistent with proof that in formal one-dimensional flow vent gain violates second law of thermodynamics. Logical and consistent way to reduce solid rocket data when pressure-time history is not neutral was derived. Since current techniques are not self-consistent in this situation, these results open door to reclamation of performance data heretofore rejected.